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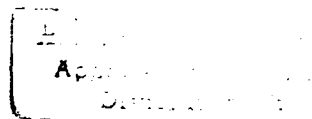
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INTERFACIAL AND THIN FILM CHEMISTRY IN
ELECTRON DEVICE FABRICATION



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<p>A. (MBE) Growth and Devices: During the last year, we have developed and optimized the MBE growth parameters for the polytype InAs/AlSb/GaSb material system. Various device structures based on this material system have been explored and have yielded excellent results. The key ideas of our devices are based on the large quantum well width possible due to the small effective mass and the very high electron velocity possible in InAs. We have demonstrated interband tunneling through an InAs quantum well as wide as 240 nm, and demonstrated a new field effect transistor structure based on AlGaSb/InAs with the highest predicted transconductance. In the area of materials growth, we have observed a universal C(8x2) reconstruction for III-V compound semiconductors, and evidence indicates that growth conditions under which the C(8x2) can be generated will yield the best structural perfection of the material.</p> <p>New materials techniques to achieve high performance GaAs charge-coupled devices have been investigated. 1) A 50-stage four-phase capacitive gate GaAs CCD has been demonstrated at 1 GHz which exhibits charge transfer efficiency (CTE) better than 0.999 and dark current lower than 10</p>					
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nA/cm². This is the highest performance device of this type yet reported. 2) A Cr-SiO film based resistive gate GaAs CCD process has been developed. Fabricated devices exhibit high CTE and low leakage current. The properties of the e-beam evaporated thin film on GaAs were investigated. 3) A new recessed-gap structure was investigated through simulation and then verified through experiment. The structure solves an outstanding problem in CTE with capacitive gate CCDs. 4) A new resistive gate CCD structure based on a semiconductor heterojunction gate has been demonstrated for the first time.

Use has been made of deep-UV light to enhance the oxidation rate of GaAs and we have found that the Schottky barrier height can be varied over a wide range. We attribute the result to the unpinning of Fermi level in the oxidized surface. In addition, we have studied the interface diffusion in a high-Tc superconductor-silicon system and found that silicon inhibits the onset of superconductivity. The effect is then employed to develop fine-line patterns (~2mm) of superconductors by selectively reacting silicon with YBCuO films.

B. Laser Surface Interactions: New physical mechanisms for light-induced reactions on semiconductor surfaces have been investigated. For example, a basic study has shown that internal photoemission from GaAs to its surface oxide is responsible for the rapid rate of UV laser enhanced oxidation of GaAs. In this study a new surface technique for studying ion movement during oxide growth was developed. Finally, a new program on laser etching of SiC has begun.

Laser assisted etching of copper was investigated using in situ Raman spectroscopy. Laser etching of GaAs was studied at temperatures below ambient to avoid background reactions. The Ge-Si laser deposition project was completed and new spectroscopic studies of Ge-Si alloys begun. Studies of stresses and strains in laser heated thin films also continued.

A new noncontacting method of measuring the properties of space-charge depletion layers at semiconductor surfaces has been developed. This technique is based on the fact that when a femtosecond optical pulse is absorbed at the surface of a semiconductor, a rapid photocurrent current transient is produced due to the internal field associated with the space charge depletion layer arising from band bending due to surface states.

C. Fundamentals of Processing Gas/Surface Interactions: Experiments have been performed to study the basic chemical dynamics of chlorine atom/hydrocarbon chemical reactions. Data obtained strongly indicate that Cl atom attack on deuterocyclohexane results in a collinear transition state which ejects DCl with very little angular momentum but high translational energy. The same apparatus has been used to develop a new technique for studying electron/molecule collision processes of importance in plasma reactors. Electrons are made by two photon photoionization, and electron scattering is investigated by following the molecular states with an energy resolution of 10⁻⁸ eV. Vibrational energy exchange with surfaces has been studied using a variant of the same technique.

Photochemical reactions of molecules adsorbed on surfaces have been investigated. Interfacial chemistry of dry zeolites, porous molecular sieve materials, and aqueous slurries of alumina have been studied. In the case of zeolites the modification of photochemical reactivity of photochemically produced radicals by adsorption on the porous solid internal surface have been demonstrated.

SUBJECT TERMS cont'd (Block 18)

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ABSTRACT (Block 19, Report Documentation Page)

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SUBJECT TERMS (Block 18, Report Documentation Page)

Raman spectroscopy	GaAs oxidation
copper	GaAs Schottky barrier
gallium arsenide	superconductors on silicon
etching	patterning
laser processing	metal alkyl
germanium-silicon alloy	AlGaSb
photodeposition	InAs
stresses	AlSb
strains	GaSb
molecular beam epitaxy	photoresists
heterostructure	electronic chemicals
tunneling device	oxidation
field effect transistors	
photochemistry	
interfacial chemistry	
porous solids	
zeolites	
alumina	
GaAs CCD	
charge-coupled device	
imager	
dark current	
resistive-gate	
femtosecond spectroscopy	
surface states	
photoconductivity	
chlorine atoms	
Cl, D ₂ S, DCl, C ₆ D ₁₂ , S ₂ Cl ₂	
chemical reactions	
transition state	
cold rotations	
hot vibrations	
diode lasers	
excimer lasers	
collision dynamics	
electron scattering	
surfaces	
SiC	
diamond	
GaAs	

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I. DIRECTOR'S OVERVIEW

A. Introduction

The third year of the Navy URI program has been particularly successful in yielding new and unexpected technical results on the surface science and chemistry of electronics materials. This work includes a strong series of publications by Wen Wang delineating the MBE growth of new tunnelling structures based in As/GaSb and AlSb based heterostructure materials. This material system is potentially very useful for the next generation of high speed and infrared photodetector applications. His work has also achieved understanding of the fundamental surface reconstruction of these semiconductors. Eric Fossum has demonstrated the first resistive gate CCD structure based on a semiconductor heterojunction gate.

In addition, Dave Auston has discovered a new and very general electromagnetic effect associated with femtosecond excitation of semiconductor surfaces; the effect provides an important method of probing surface band bending. George Flynn's work has yielded a new method of measuring the cross sections for electron excitation of molecular vibrational modes. Such processes play an essential role in the determination of the chemical reactions and electron energy distribution in a plasma etching or deposition system. Incidentally, both Auston and Flynn were recognized for their work in their respective areas by being asked to write articles for *Physics Today* and *Science*, respectively.

Finally, Rick Osgood's study of UV-enhanced oxide growth on GaAs has yielded insight into the basic mechanisms of light-enhanced surface reactions. In this case, the threshold dependence argues that internal photoemission is playing a major role in the enhanced oxide growth. Ed Yang has collaborated on this work by clearly showing how Schottky barrier height changes can be observed with this oxide. He has also begun a new series of experiments investigating patterning and contact formation on high-T_c superconducting materials.

Both Irving Herman and Rick Osgood have demonstrated new forms of laser-assisted chemical processing. Herman has shown a new direct-write method of etching copper based on a cw-laser-initiated chlorine reaction. This reaction was studied for the first time with Raman spectroscopy. Osgood's group has begun the search for an effective laser technique for etching SiC. Finally, Nick Turro's expertise in organic photochemistry has provided important insights for Flynn and Osgood in their work on basic interfacial chemical dynamics. Turro's research group is developing new photochemical methods to investigate reactions which occur at interfaces and mechanisms of the actions of photoresists.

B. Objective

The objective of this URI research program is "to form an interdisciplinary research center to study several prominent classes of interfacial reactions which are important in the fabrication of submicrometer circuits and devices."

The ONR/URI funding has enabled Columbia to establish this new interdisciplinary research center on campus, the Microelectronics Sciences Laboratories (MSL). This center draws from the resources of three departments--Chemistry, Electrical Engineering, and Applied Physics. It has directly enabled three well known scientists to initiate their university research careers at Columbia: Professor Wen Wang, Professor Irving Herman, and Professor Dave Auston. In addition, two new junior professors have initiated research in the surface chemistry of electronics materials. Their research has been aided indirectly by the equipment and research orientation at Columbia established by the ONR program: Professor Robert White, polymers for packaging (Department of Electrical Engineering) and Professor Brian Bent, the surface chemistry of CVD growth (Department of Chemistry).

In this third year of the program, we are proud to realize a full program of research accomplishments from the above and other original Columbia faculty members.

C. Capital Equipment

The following capital equipment was purchased with this years funds:

1. Plasma Insulator Deposition System
2. Digital Oscilloscope
3. Small Upgrade of MBE Machine:
 - a. Alloying Furnace
 - b. New Cracking Effusion Cell
4. Device Characterization Tools:
 - a. 1 Manual Scriber
 - b. Semiconductor Parameter Analyzer

D. Contacts with Navy Laboratories and Industry

1. Naval Laboratories and within MSL

Our most extensive interactions with Naval personnel continue to be with both NRL and ONR.

- a. Contacts

Professor R. Osgood has had discussions with Jim Horwitz, Chemistry Division at NRL on UV photodissociation of TMAI; and Martin Kabler, Optical Division at NRL on determining band bending on surfaces

Professor N. J. Turro received a visit in his labs from Harold Guard and Robert Grasselli from ONR.

Professor Fossum has had discussions with Dr. Woody Anderson and Dr. Nelson Saks from the Naval Research Labs on CCD technology.

Professor Flynn visited and gave a seminar at the Naval Research Laboratories in 1988. He also served on the Navy Scientific Evaluation Panel in Washington in 1988.

James Butler from the Naval Research Laboratories gave a seminar, "IR Spectroscopy and Diagnostics of Chemical Vapor Deposition," at Columbia on our MSL Seminar Series.

b. Collaborations

Professor W. Wang has collaborated with Dr. Ben V. Shanabrook (NRL) on the influence of strain on the optical properties of GaSb/AlSb(111) quantum wells; Drs. Ben V. Shanabrook, Evan Glaser, and Tom Kennedy (NRL) on the characteristics of band edge and trap luminescence of MBE epitaxial AlSb; and Dr. Robert J. Wagner on the measurements of the effective mass of two-dimensional holes by cyclotron resonance in p-type modulation-doped AlSb/GaSb heterostructures.

Professor I. Herman collaborated with several internal groups in using Raman analysis to study interface and thin film processing in microelectronics. In addition, Si thin film membranes supplied by Dr. Palik, recently of the Naval Research Laboratory, were analyzed by Raman scattering.

2. Industries

Professor D. Auston has initiated several collaborative projects. A collaboration with Richard Nottenburg and Young-Kai Chen of AT&T Bell Laboratories was initiated this year to measure the properties of very high frequency heterojunction bipolar transistors using optoelectronic probing techniques. In addition, a collaboration with David Haas and Harris Goldberg of the Hoescht-Celanese Corporation was initiated to evaluate new electro-optic polymer materials for high speed modulation. A collaboration with Paul Ferm of the Allied Signal Corporation was initiated this year to evaluate

the properties of new organic nonlinear optical materials for applications to very high speed modulation.

Professor Eric Fossum has collaborated with Dr. Raj Sahai from the Rockwell Science Center; Dr. Jerry Woodall, Dr. Peter Kirchner, and Dr. Michael Tischler of IBM Research; and Dr. Frank Grunthaner and Dr. Joseph Maserjian from NASA/JPL.

Over the past year, Professor Yang has continued his work on the high T_c superconducting thin films in collaboration with Dr. Chin-An Chang at IBM Watson Research Center. His goal in this area is to develop the high-speed superconducting interconnects and transmission lines for electronic and communication applications.

Both Professor Osgood and Herman have continued their numerous industrial interactions on research in laser processing and diagnostics. In this last, the most notable new emphasis is in the use of lasers for processing of electronic packaging materials. In this area, they have interacted with IBM, Motorola, SRC, and Honeywell. Osgood has initiated a new program in laser-assisted semiconductor surface chemistry with IBM, and Herman has continued in his development of new direct-write diagnostics.

Professor Turro has had continued collaborations in zeolite research with chemists V. Ramamurthy and David Corbin at DuPont and Michael Drake at Exxon. Research on the basic mechanisms of novel photoresists have been initiated with Nigil Hacher and Kevin Welsh of IBM.

Finally, MSL has continued its widely publicized MSL Seminar Series. The prime participants in this program have been speakers from the many fine major industrial labs near Columbia.

E. IBM Program

The ONR-URI program at Columbia was originally matched with Columbia's IBM program in electronics Materials and Materials Processing. This original match has continued to have concrete intellectual feedback into the ONR program. In particular, Professor White's program (supported only by IBM) in polymer interfacial chemistry has provided added emphasis in our emerging interest in

the difficult materials of advanced electronic packaging. In addition, Professor Wu's knowledge of high-Tc superconducting materials, again supported heavily by IBM, has helped Professor Yang to develop a new program in this area.

Professor Turro has initiated a program to elucidate the basic mechanisms which operate on photolysis of novel photoresists. In particular, photoresists that produce strong acid upon photoexcitation are being studied in order to establish the products formed, the intermediates produced and the kinetics of critical steps.

II. PROGRESS REPORTS

A. MBE Growth and Devices

1. Heterostructures Grown by Molecular Beam Epitaxy (Professor Wen Wang)

Achievements by Professor Wang's group include the following:

- a. First observation of resonant tunneling in the InAs/AlSb heterostructure system, with the longest coherent distance quantum wells (24 nm) ever reported, Appl. Phys. Lett. 53, 2320 (1988).
- b. First observation of room-temperature negative differential resistance in InAs/AlGaSb single barrier heterostructures, Appl. Phys. Lett. 54, 1899 (1989).
- c. Observation of a factor of two improvement in the peak-to-valley ratio in (111)-oriented AlAs/GaAs/AlAs double barrier tunneling structures compared to samples grown in the (100) direction, due to the larger X-valley effective mass of the AlAs in the (111) direction. A larger effective mass leads to a reduction in the barrier transmission probability and a decrease in the leakage current due to inelastic tunneling. Appl. Phys. Lett. 54, 2133 (1989).
- d. First observation of resonant tunneling of holes in the AlSb/GaSb/AlSb material system, demonstrating that the valence band offset is large (approximately 0.4 eV) between GaSb and AlSb. This material system is therefore useful for near infrared optoelectronic devices applications. Appl. Phys. Lett. 55, 694 (1989).
- e. Fabrication of the first InAs channel field effect transistors, and proposal of an InAs FET with an order of magnitude higher transconductance than AlGaAs/GaAs HEMTs. Appl. Phys. Lett. 55, 789 (1989).

f. Demonstration of the first interband tunneling in the InAs/AlSb/GaSb material system. The single barrier structure (InAs/AlSb/GaSb) does not need to be doped, therefore is easier to fabricate than the tunnel diode, which has serious impurity diffusion and segregation problems due to the heavy doping. The double barrier structure (GaSb/AlSb/InAs/AlSb/GaSb) has a much better peak-to-valley current ratio than the conventional resonant tunneling diode due to the fact that band gap blocking of non-resonant carriers is much more efficient than the momentum blocking, and is promising for applications to three terminal devices because of the very wide quantum well that can be achieved. Appl. Phys. Lett. accepted for publication (September 1989).

g. Demonstration of quantum tunneling through an InAs quantum well as wide as 240 nm in a resonant interband tunnel diode, paper accepted for presentation at the International Electron Device Meeting (IEDM), Washington, D.C., December 1989. (Best paper selected by the Program Committee.)

h. First observation of a two-dimensional hole gas in the AlSb/GaSb modulation-doped heterostructure, and the performance of complementary logic would be better in this material system than in the AlGaAs/GaAs system, Appl. Phys. Lett. accepted for publication (September 1989).

i. First observation of negative differential resistance in a single barrier GaAs/AlAs/GaAs heterostructure, and demonstration of the importance of band symmetry in the quantum confinement of electrons, Appl. Phys. Lett. 55, 1555 (1989).

j. Studies of the surface structures of GaSb, AlGaSb, and alternating GaSb/AlSb layers using 10 kV reflection electron diffraction. The materials were grown from elemental Ga and Al, and Sb₄ sources. We have observed that the C(2x6) structure is the dominant surface phase for substrate temperatures between 400°C and 600°C under Sb-stabilized conditions. Above 540°C, depositing

sub-monolayer quantities of Ga on the Sb-stabilized surface changed the C(2x6) pattern to (1x3). With further Ga deposition the pattern changed to C(8x2), a Ga-stabilized surface. The C(8x2) Ga-stabilized surface, which has been observed on all other III-V arsenides, phosphides, and antimonides, was previously thought not to exist on GaSb. Our observation indicates that the C(8x2) metal-stabilized surface is common to all III-V compounds, suggesting that bond-pairing occurs on all III-V surfaces and is thus a universal reconstruction for surfaces of tetrahedrally coordinated semiconductors. This work was presented at the 10th MBE workshop, September 13-15, 1989, North Carolina State University, Raleigh, N.C. The paper will be published in J. Vac. Sci. Tech. March/April issue (1990).

k. Determination of the heavy-hole mass for quantum confinement in the (111) direction using resonant Raman scattering in collaboration with Dr. B.V. Shanabrook of Naval Research Laboratory, demonstrating that the heavy-hole mass is the largest for this orientation. Correspondingly, the in-plane heavy-hole effective mass is the smallest. As a result, (111) quantum well lasers theoretically have the lowest threshold current density of any orientations. Phys. Rev. B 39, 3411 (1989).

2. High Performance GaAs Charge-Coupled Devices
(Professor Eric Fossum)

GaAs CCD's are important in many demanding signal processing applications because of their high speed, low noise and radiation hard capability coupled with their compatibility with III-V electro-optic devices. Potential applications include radar signal processing, spatial-light modulator (SLM) multiplexers, high-speed readout for acousto-optical tunable filters (AOTF), fast-in/slow-out signal acquisition for high-speed sampling, and for multiplexers in advanced IR, UV and X-ray image sensors.

We have been investigating GaAs CCDs for several of these applications, and in particular, have focussed on the interaction of device structure, material structure, and device architecture. For high-speed applications, the resistive gate structure is preferred. We have developed our own e-beam evaporation process for the formation of a Cr-SiO cermet film with the proper resistivity. The properties of this film which were investigated include transmission, composition, temperature dependence of resistivity, and electrical properties of the cermet-GaAs contact (Schottky-like). Although Rockwell used a sputtered cermet film in their CCDs, characterization of the film was not completed. We have shared our results (at their request) with them. The results were subsequently published in IEEE Trans. Electron Devices.

An alternative to a cermet film is the use of a semiconductor film. In collaboration with J. Woodall and P. Kirchner at IBM Research, we have investigated the use of an InGaAs film as a resistive gate material. The In GaAs was grown (3-D growth) on a GaAs CCD channel structure. Sheet resistance was typically 20 k-ohm/sg. MESFETS using this film operate well. Preliminary results indicate CCDs operating at 12.5 MHZ with a CTE of 0.86. We now believe that the resistive gate structure must be altered to improve CTE. (Conventional CCDs built on etched-back material show CTE exceeding 0.999 at 1 GHz).

Capacitive gate CCDs are important in imager architectures for lower power consumption and as transfer gates into a resistive gate serial channel. Since overlapping gates lead to low gate-to-gate breakdown voltage (through the channel), the open gap region can lead to potential troughs in the channel and thus reduce CTE. We have discovered a new method to eliminate the trough and significantly improve CTE. In this method, the region between the gaps is recessed by wet chemical etch. Good agreement between modelling and experimental results has been obtained.

For imager applications running at relatively low clock speeds, the leakage current of the Schottky gate contact contributes substantial dark current. We have found that the use of an AlGaAs

cap layer (400 Å) can reduce the dark current by over four orders of magnitude to levels found in Si CCDs.

We are presently shifting our attention from high speed GaAs CCDs to low speed imager architectures. In this way, engineered bandgap detectors for SWIR and LWIR may utilize the GaAs CCD as a multiplexer. High CTE and low dark current continue to be dominating issues. This work is being done in collaboration with F. Grunthaner and J. Maserjian at NASA/JPL.

3. Interface Chemical Modification of Metal on Superconductor-Semiconductor Systems
(Professor Edward Yang)

In the past year, we have directed our research effort in interface chemical modification diffusion and reaction in metal-semiconductor and superconductor-semiconductor systems. Experimental results have led us to some surprising applications. In a metal-GaAs interface, the Fermi level movement is observed to be significantly wider in deep UV-enhanced oxidized surfaces. In the YBaCuO/Si system, interdiffusion that destroys superconductivity is found to be useful for fine-line patterning.

a. Chemically Modified GaAs Schottky Barriers

We have reported a GaAs surface treatment using deep ultraviolet (UV) light ($h\nu \geq \text{eV}$) to enhance the reaction of oxygen with GaAs prior to metal deposition.^{1,2} In these experiments, metals from a wide range of work function were deposited on GaAs surfaces with ~2 monolayers of stoichiometric native oxide formed with 248 nm light, referred to as ST surfaces. Other surfaces were annealed to form Ga-rich oxides prior to metal deposition, referred to as GR surfaces. Figure 1 shows the Schottky barriers for a wide range of metals on clean and modified n-GaAs surfaces. Also shown is a representative pinning level and the ideal Schottky limit ($\phi_{\text{SB}} = \phi_{\text{m}} - \chi_{\text{GaAs}}$). The Schottky barriers for the clean and various modified

contacts were determined by current-voltage (I-V) measurements, and the barrier height variation was confirmed using room temperature photoresponse measurements.¹ Nearly all of the contacts had ideality factors less than 1.1, indicating that an interfacial insulating layer was not affecting the current-voltage relation. The arrows in Fig. 1 indicate the trend in barrier variation for contacts on the deep UV oxidized surfaces from the contacts on clean surfaces. There is a clear trend toward the ideal Schottky limit for the surfaces photo-oxidized prior to metal deposition. The Schottky barrier height variation in Figure 1 is very large for several metals, providing information on the increased Fermi level movement in the GaAs bandgap.

In examining how chemical modifications of GaAs interfaces can affect the Fermi level position, several possibilities must be considered. We have considered three effects which chemical modification of the interface could have. First, new states could be created which will increase the charge at the interface. If the net increase in charge is not zero, the increase in positive or negative charge will affect the depletion layer of the semiconductor, thereby affecting the Fermi level. Second, the total number of states at the interface could be reduced. This would allow the Fermi level to move through a larger energy range while accommodating the charge necessary to reach equilibrium when the semiconductor is in contact with another material. The reduction in the density of states is the goal of most attempts to passivate GaAs surfaces since it would allow MIS device possibilities. However, the Fermi level pinning behavior can also be affected in a third way if a chemical modification of the surface alters the distribution of states at an interface. It is possible that the range of Fermi level movement can be increased while the total number of interface states is not reduced. If the energy distribution of the states at the interface is modified to shift acceptor-like and donor-like levels in the GaAs bandgap closer to the band edges, the Fermi level will move through a wider region of the bandgap before charging these states.

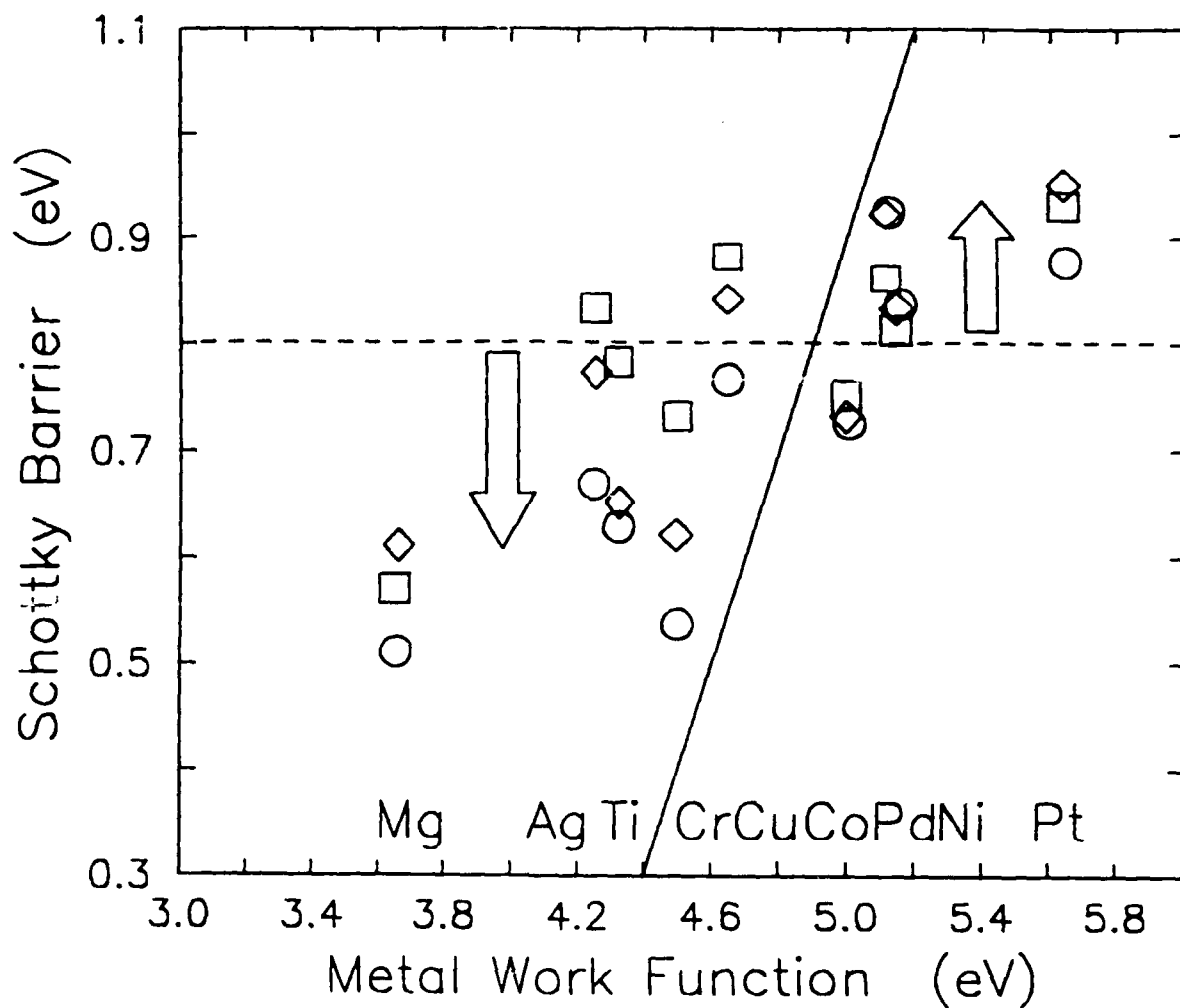


Figure 1: Schottky barrier heights versus metal work function for metals deposited on clean surfaces (\circ), stoichiometric deep UV light formed oxides (ST) (\diamond), and Ga-rich oxides formed by annealing deep UV light formed oxides (GR) (\square). The dashed line is a pinned interface limit, and the solid line is the ideal Schottky limit. Arrows indicate the trend in barrier variation for the modified interfaces.

To consider the systematic barrier variation observed in Fig. 1 for the GaAs surfaces oxidized by deep UV light prior to metal deposition, we have used a phenomenological model as presented by Duke and Mailhot,³ and also by Zur, McGill, and Smith⁴ to understand the effect of modifying the interface state distribution on the Fermi level position at the GaAs surface. This simple, analytic model allows us to compare the effects of modifying the interface state density and energy distribution. In this formalism, charge centers are assumed to exist in the semiconductor near the metal/GaAs interface. The centers have activation energies such that when the Fermi level crosses this energy, the charge occupancy of the centers changes with a Fermi-Dirac distribution. The occupation of the centers by positive or negative charge can restrict the Fermi level position at the metal/GaAs contact if the density of centers is sufficient.⁴ The only two parameters which have a strong effect on the calculation of the Fermi level are the density of interface states and the energy position of the states. The other parameters in the model can vary throughout a wide range of physically possible values without significantly affecting the results of the calculation.

The Fermi level position in the GaAs bandgap for the various metals on ST and GR prepared n-type substrate relative to the conduction band minimum are again shown in Figure 2 versus the work function of the contact metal. For the dashed line, the activation energy to donate charge (i.e. centers become positively charged) is $E_d = 0.5$ eV relative to the valence band maximum (VBM) of GaAs, and the activation energy to accept charge (i.e. centers become negatively charged) is $E_a = 0.7$ eV assuming centers with three-charge-states of density 10^{14} cm⁻².

It has been shown that these energies and density describe the empirical behavior of the Schottky barrier for metals on clean GaAs. That is, they are consistent with the GaAs Fermi level being restricted to a narrow midgap range. The solid "S" shaped curves in Fig. 2a and 2b are found by varying the activation energies to get a least-squared fit to the data. These "S" shaped curves have been calculated assuming the same high density of states (10^{14} cm⁻²) as the dashed curves.

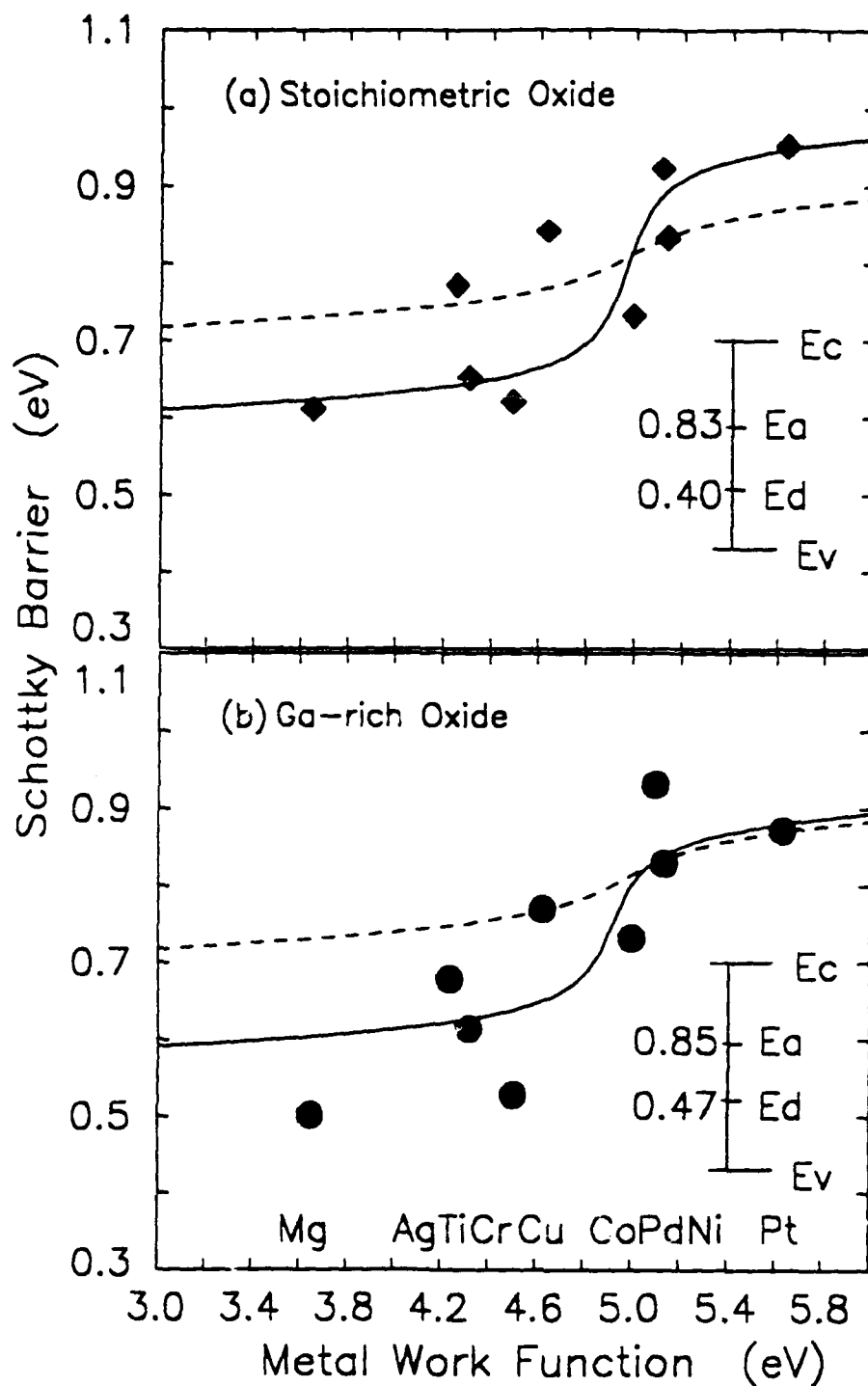


Figure 2: Schottky barriers from Fig. 1 for various metals on deep UV oxidized n-GaAs. The dashed curve is for conditions from clean GaAs ($E_a=0.7$ eV, $E_d = 0.5$ eV, $N_s = 10^{14}$ cm $^{-2}$). The acceptor and donor energies from the fit are shown in the insets. (a) Data for ST surface preparation. (b) Data for GR surface preparation.

For all of the deep UV oxidized interfaces, changing the activation energies in the calculation instead of reducing the density of the charge centers results in a weak dependence of barrier on metal work function for high and low work function metals. Therefore, the best fit to our data is achieved by using a high density of states in all cases, while changing the energy distribution of the states. This is in agreement with reverse bias and forward bias capacitance measurements of the modified interfaces which indicate that a high density of interface states exist even for the interfaces which show the largest barrier variation.

The most important conclusion from this study is that the increased variation of the Schottky barrier we have observed on UV oxidized GaAs is best explained without a reduction in the density of interface states. The change in the activation energies of the interface states which accounts for the variation has been attributed to interatomic charge redistribution due to the electronegative nature of oxygen. While the precise role of photochemistry in effecting the barrier variation we have observed is not known, it is clear that light can play a large role in affecting metal/GaAs interface formation.

b. Interdiffusion and Patterning of YBaCuO Films on Silicon

In the preparation of the high T_c superconducting films, Cu/BaO/Y₂O₃ layers are deposited in sequence on a substrate by electron-beam evaporation. The sample is then heat-treated in a rapid thermal annealer (RTA) in flowing helium and oxygen. The technique is developed at Columbia where a zero resistance temperature is found to be 84K for films on an MgO substrate. However, the electrical properties of the films on silicon substrate depend strongly on the RTA temperature and duration. With a 30 second annealing time, the film behaves like a semiconductor after a low temperature anneal but becomes insulating for temperatures greater than 980°C. A superconducting transition with an onset temperature of 85°K is observed for a film undergone a 950C RTA, but its resistance does not drop to zero at lower temperatures.

Figure 3 shows the results of the Auger depth profiles of four samples annealed at different temperatures for 30s. With a 900°C anneal, the silicon and oxygen diffused slightly into each other at the interface. The Ba and Cu intermixed, but not the Y as shown in Fig. 3(a). The resistivity of such a sample was semiconductor-like. This may be due to the incomplete mixing of the elements. With a higher temperature anneal, all the elements mixed well and Si diffusion into the film became severe, as shown in Fig. 3(b). Superconductivity with onset of 85K was seen from this sample, but the transition was not complete. Further increase of the anneal temperature turned the film into an insulator. As seen in Fig. 3(c), silicon diffused almost into the entire film.

To overcome the silicon diffusion, a thin (1000 - 2000 Å) Ag or Au layer has been used as a barrier. The results were successful and superconductivity with T_c of 74K was observed. Fig. 3(d) shows the Auger depth profiles of the film with 2000 Å Au barrier. In contrast to the film without a barrier shown in Fig. 3(b), the Si was not seen in the surface portion of the film. This portion without Si is responsible for the observed superconducting transition. Thus, under the same RTA conditions a metal barrier layer reduced the silicon diffusion effectively.

c. High T_c Superconducting Thin Films

Over the past year, we have continued our work on the high T_c superconducting thin films in collaboration with Dr. Chin-An Chang at IBM Watson Research Center. Our goal in this area is to develop the high-speed superconducting interconnects and transmission lines for electronic and communication applications. It has been reported that using superconducting material to replace existing metal lines, at 77 K the power dissipation in an electronic circuit is reduced and the signal processing speed in a communication system is increased.

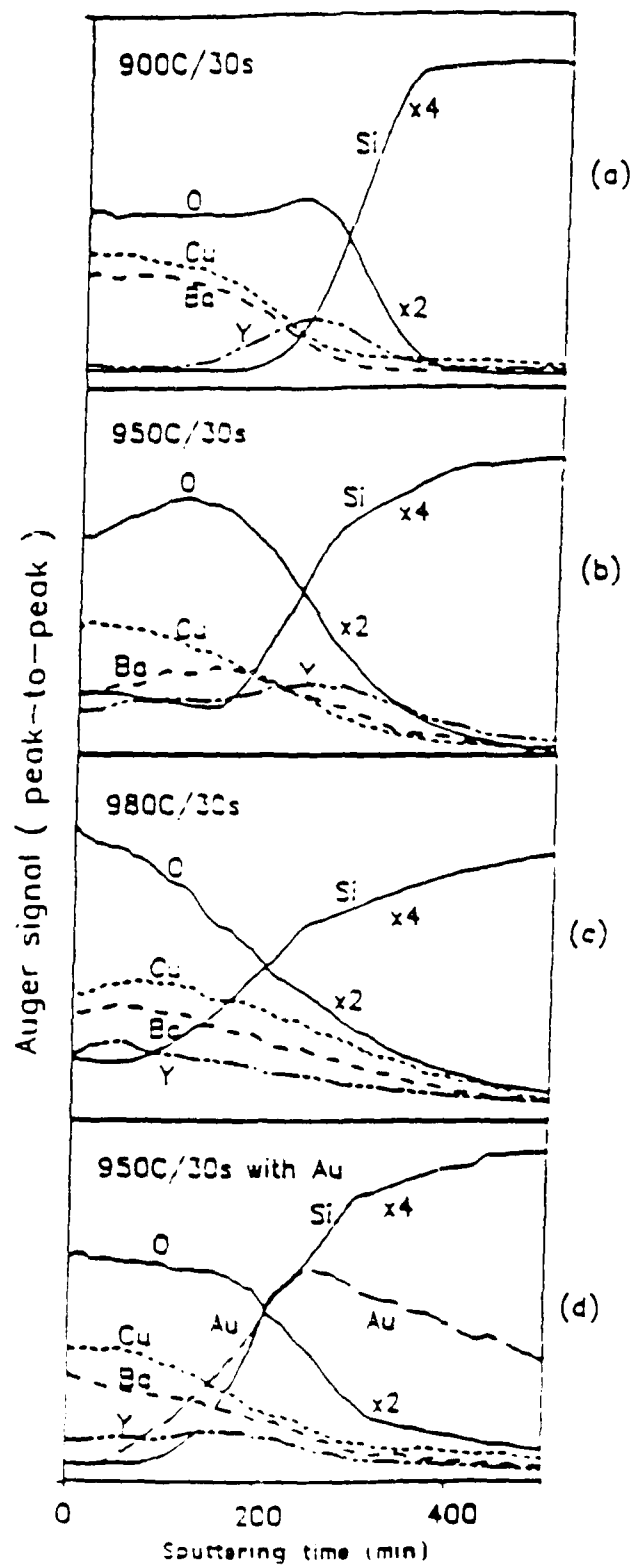


Figure 3: Auger depth profiles of the YBaCuO films on Si annealed for 30s at (a) 900°C, (b) 950°C, (c) 980°C, and (d) 950°C with a Au barrier layer.

Much progress has recently been made in the following three areas. First, we continued to develop a simple, rapid and reliable technique of making high T_c superconducting thin films. By combining rapid thermal annealing and electron-beam evaporation, we are able to fabricate large scale samples over a very short time period. Several substrates (MgO , Al_2O_3 , SiO_2 , and Si) have been used for studying the interdiffusion and reaction at the film-substrate interface. We found that MgO is the most suitable substrate and Si is the worst. To overcome the Si -film interaction, a thin metal buffer layer has been deposited between the film and a substrate. With a buffer, the superconducting films have been made on a silicon substrate.

Second, in order to turn the films into designed line structures and device features, we invented a novel method of patterning the superconducting thin films. This method is based on inhibition of superconductivity by impurity-film intermixing in which sophisticated silicon lithography and laser-etching techniques have been utilized for patterning superconducting films. In comparison with conventional patterning methods, this technique has its advantages in fabricating both micron-sized structures and large-scale features without chemical contamination to superconducting films. We have successfully demonstrated several micron-sized line and device structures patterned on MgO with T_c above 77 K. More interestingly, this method could be extended to pattern the buffer layer on a Si substrate, thus providing us with a potential way of making superconducting interconnects on a silicon chip.

Third, we have explored metal-superconductor (M-S) contacts. Various metals (Ti , Pt , Au , Ag , Cu , Sn , and Al) have been investigated. We have found that reactive metals such as Ti disrupt the superconductor, resulting in an insulating layer at the interface. Less disruption has been observed when inert metals such as Ag were used. The importance of this work is not only to study the chemical interaction at the contacts, but also to find suitable low resistant metal contacts to the superconductor. Technically, low resistance metal contact at low temperature is a basic requirement for applications of the high T_c superconductor materials to electronics.

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B. Laser Surface Interactions

1. Laser Alteration of Surface Chemistry in Electronic Processing
(Professor Richard M. Osgood, Jr. and Postdoctoral Research Scientist, Dr. Mike Schmidt)

We have continued our study of the deep UV light enhanced oxidation of GaAs concentrating on the chemical state of the reacted species and on the role of photogenerated electrons in the reaction mechanism. Using the monochromatic Al K α x-ray source of our Kratos surface analysis system, we have been able to better resolve the XPS spectra of the GaAs/oxide formed under UV irradiation.

In addition, we have begun examination of two new projects associated with light assisted chemistry on semiconductor surfaces. In one we are beginning the study of excimer-laser-assisted etching of SiC material. This project is cosponsored by a small local company interested in piezoresistive sensors. Thus far we have demonstrated that etching can occur, and we have obtained preliminary data on its fluence and pressure dependence. In the second project, we are preparing to study the effects of light-enhanced ECR processing of semiconductors. This project is cosponsored by IBM, which has donated the UHV connected ECR source. The project is initially focussed on studying nitriding of GaAs.

Finally we have concluded our investigation of the basic photochemical cross section for surface-adsorbed metal alkyls. These

experiments have provided some of the first studies of photochemical yields on semiconductor surfaces.

a. Fundamental UV Mechanism of GaAs Oxidation

In our main project this year, we have characterized the As-oxides on the GaAs surface after UV-enhanced oxidation. By curve fitting to the As_{2p_{3/2}} spectra for GaAs surfaces with oxide coverages from submonolayer to ~10 monolayers, we can determine the chemical state of As in the oxide. From literature values, we are able to correlate the chemical shifts of the oxidized As peaks with As³⁺ in As₂O₃ and As⁵⁺ in either As₂O₅ or GaAsO₄. XPS is not able to distinguish between the two As⁵⁺ molecules. The As³⁺ species has a chemical shift from the substrate As³⁺ of ~3eV, while the As⁵⁺ is shifted ~4.5 eV. These shifts are well resolved in our spectra. Spectra at increasing oxide coverage indicate that for deep UV enhanced oxide, As is almost exclusively in the As³⁺ state for the initial ~2 monolayers of oxide; then the As⁵⁺ oxide species increases more rapidly than the As³⁺, up to 5-6 monolayers; after this coverage, both the As³⁺ and As⁵⁺ increase at nearly the same rate.

We are planning to perform similar experiments for low temperature thermal oxides (450°C) to see if similar growth characteristics are observed. This is important because the As⁵⁺ state has been associated with the interaction of excited oxygen with GaAs, so a comparison of thermal and deep UV oxidation may help identify the light enhancement mechanism.

The chemical state of oxygen on the GaAs has also been studied with monochromatic XPS. Curve fitting to the O 1s spectra indicates two forms of oxygen on the GaAs surface. From the literature, the two species have been identified as fully dissociated and a molecular-like species, consistent with the "side-on," peroxo configuration. For ~1 monolayer coverages, there is about an equal amount of each oxygen species on the GaAs surface. For thicker coverage, the fully dissociated form of oxygen increases, while the amount of the molecular-like species remains constant. We are currently performing experiments to study the interaction of light

with the molecular-like oxygen species. We are particularly interested in the possibility that the molecular-like species is a precursor to fully dissociated oxygen.

An issue of central importance to an understanding of the enhancement mechanism is knowing whether direct photon absorption by an adsorbate or precursor enhances the reaction, or whether energetic photoelectrons are involved. We then performed experiments to study the photoemission of electrons from GaAs, and found a photon threshold of 5.1 ± 0.1 eV for electron emission from our sputtered and annealed surfaces (yield 5×10^{-5} e-/photon), which compares well with published data from cleaned GaAs (threshold 5.4 eV, yield 1×10^{-4} e-/photon). For a surface with 5 - 10 Å of oxide, the electron emission threshold is reduced to 4.7 ± 0.1 eV (yield 5×10^{-6} e-/photon). This suggests the possibility that energetic electrons are involved in the enhanced GaAs oxidation, but work is continuing in order to more precisely identify the role which the electrons play.

We have also submitted for publication the results of a study on the diffusion of species during the oxidation of GaAs. This study describes a new technique using a combination of the classical marker method and ion scattering spectroscopy (ISS) to study atom and ion movement during oxidation of GaAs. We have used it to show that initially UV-enhanced oxidation and thermal oxidation (450°C) proceed by the inward diffusion of oxygen. In the experiments, ~0.2 monolayer of Sn was deposited on clean GaAs and measured by ISS. Then ~10 Å of oxide was formed by either UV-enhancement or thermal oxidation. If the oxide formed by the outward diffusion of Ga or As, the Sn marker would be buried and would not be seen by ISS. It was found that the Sn remains on the surface of the oxide, so it is concluded that the oxide forms through the inward diffusion of oxygen. Our technique was also used to study the initial oxidation of Ni and Cu, where previous reports have concluded that the metals diffuse outward. This was confirmed by observations of the Sn marker signal decreasing upon oxidation of the surfaces.

b. Metal Alkyl Surface Spectroscopy

We have concluded a study of the photophysics of chemisorbed organometallic molecules using UV and IR spectroscopies. The objective of the work was to understand how dissociative optical processes are perturbed when the molecule was adsorbed on a semiconductor surface. In addition, the study has yielded valuable information on the adsorption sites and thermal reactions of molecules important in II-VI CVD growth. The results of this work have been submitted to the Journal of Chemical Physics, and an abstract of the work is presented below.

Abstract

Metal-alkyl molecules adsorbed on chemically passivated silicon surfaces have been studied by using infrared total-internal reflection as well as ultraviolet transmission spectroscopy. These submonolayer-sensitive techniques allow us to investigate the surface photophysics of both physisorbed and chemisorbed layers. For chemisorbed species, the surface hydroxyl groups have been shown to be the prime adsorption sites. In addition, temperature programmed desorption spectroscopy (TPD) and mass spectroscopy of laser induced desorption (LID) were used to determine the identity of the chemisorbed species and their fragments under ultraviolet photodissociation. The surface photochemistry was observed to be strongly wavelength dependent at 193 nm and 248 nm. The roles of both the adspecies-substrate interaction and the gas-phase photodissociation processes in this effect are discussed.

2. In Situ Optical Diagnostics of Semiconductors Prepared by Laser Chemical Processing and Other Novel Methods (Professor Irving P. Herman)

We studied the thermal and laser-assisted etching of copper films on glass by chlorine by in situ Raman spectroscopy and ex situ profilometry. Surface products of these reactions are either CuCl or

CuCl_2 , as detected by Raman analysis in Figs. 1 and 2. In many of the experimental regimes we studied, these copper chloride products formed on the surface but were not desorbed by the laser during the laser heating scan. They could be removed afterwards by rinsing in hydrochloric acid. However, some experimental regimes were discovered where these copper chlorides could be partially desorbed during processing, as seen in Fig. 3. To avoid the spontaneous reaction of copper with chlorine at room temperature, it was necessary to oxidize the copper before etching, to form a $\sim 100 - 200$ Å thick Cu_2O overlayer. This thin oxide layer was monitored by Raman analysis, as shown in Fig. 4 before, during, and after etching.

GaAs undergoes a spontaneous reaction with Cl_2 at room temperature, which leads to very fast etching at modest pressures of chlorine (> 1 Torr). Any attempt to use laser-assisted etching to pattern GaAs with this reactive gas would not be interesting because of this background reaction. We have shown that this unwanted background reaction is suppressed in the presence of 20 Torr of chlorine gas by cooling the wafer to -50°C . Using this suppression method laser-assisted localized thermal etching of GaAs by Cl_2 was demonstrated with no background, nonlocal etching.

We completed the study of Ge-Si deposition by 193-nm photolysis of germane/disilane mixtures with analysis by Raman scattering this year. The experimental analysis of Raman scattering in Ge-Si alloys as a function of temperature began this year. This study will provide basic information about Raman scattering in semiconductor alloys and will also build the data base for future optical diagnostic investigations. A furnace was set up for growing bulk Ge-Si polycrystalline material this year. It will also be used to heat the Ge-Si during Raman analysis.

During this project year we extended the theoretical investigation of stresses, strains and defect formation during laser heating of semiconductors to thin semiconductor thin films on insulators, such as glass and sapphire.

A critical review of the fundamental processes in laser-assisted deposition of thin films from gas-phase and surface-adsorbed

reactants was also conducted during this reporting period for a special Chemical Reviews issue on microelectronics.

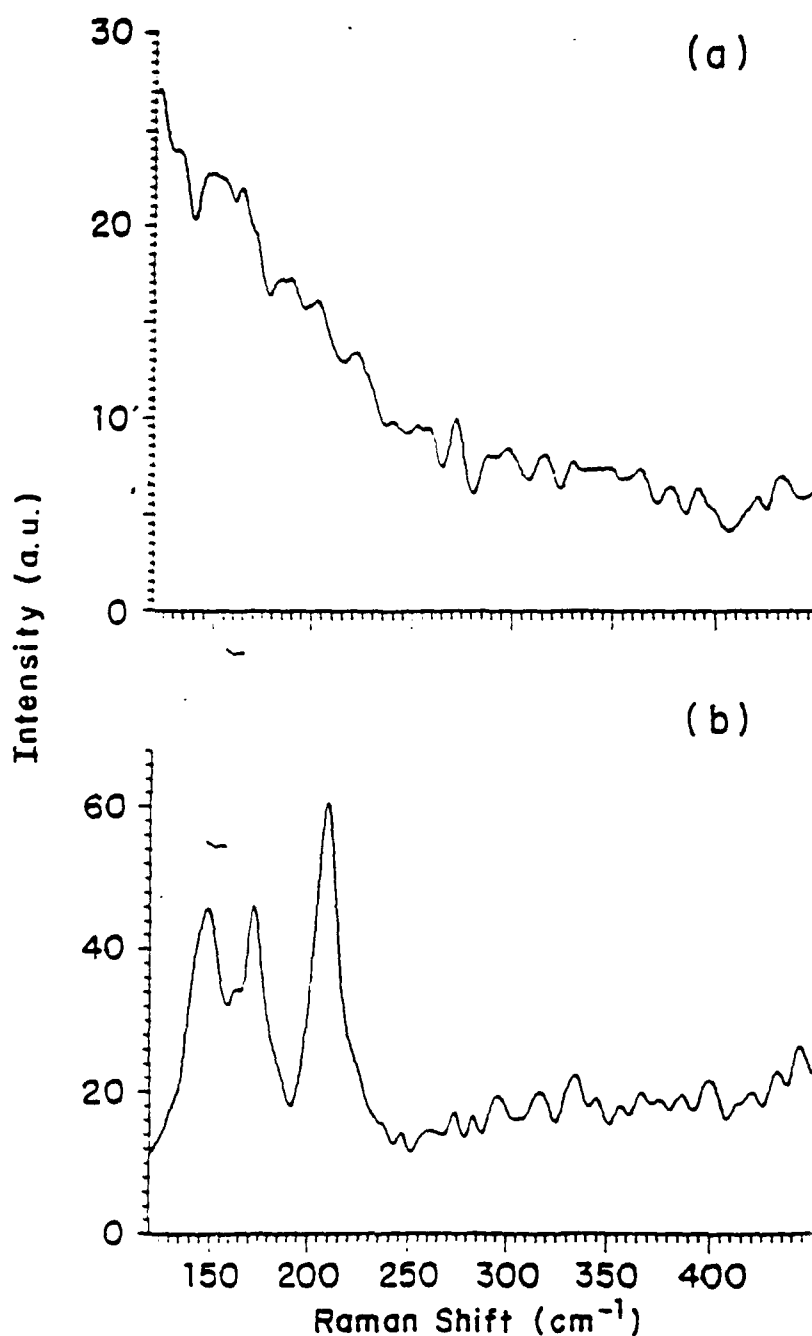


Figure 1. Raman spectrum of partially passivated copper film (1.7 μm) after exposure to 10 Torr Cl_2 for 10 minutes (4880 \AA , taken in vacuum). (a) $T=298\text{K}$, (b) $T \approx 77\text{K}$. These spectra suggest the film is CuCl . The peaks at 145, 170, and 210 cm^{-1} in (b) are the cuprous chloride LA + TA, TO, and LO phonon features, respectively.

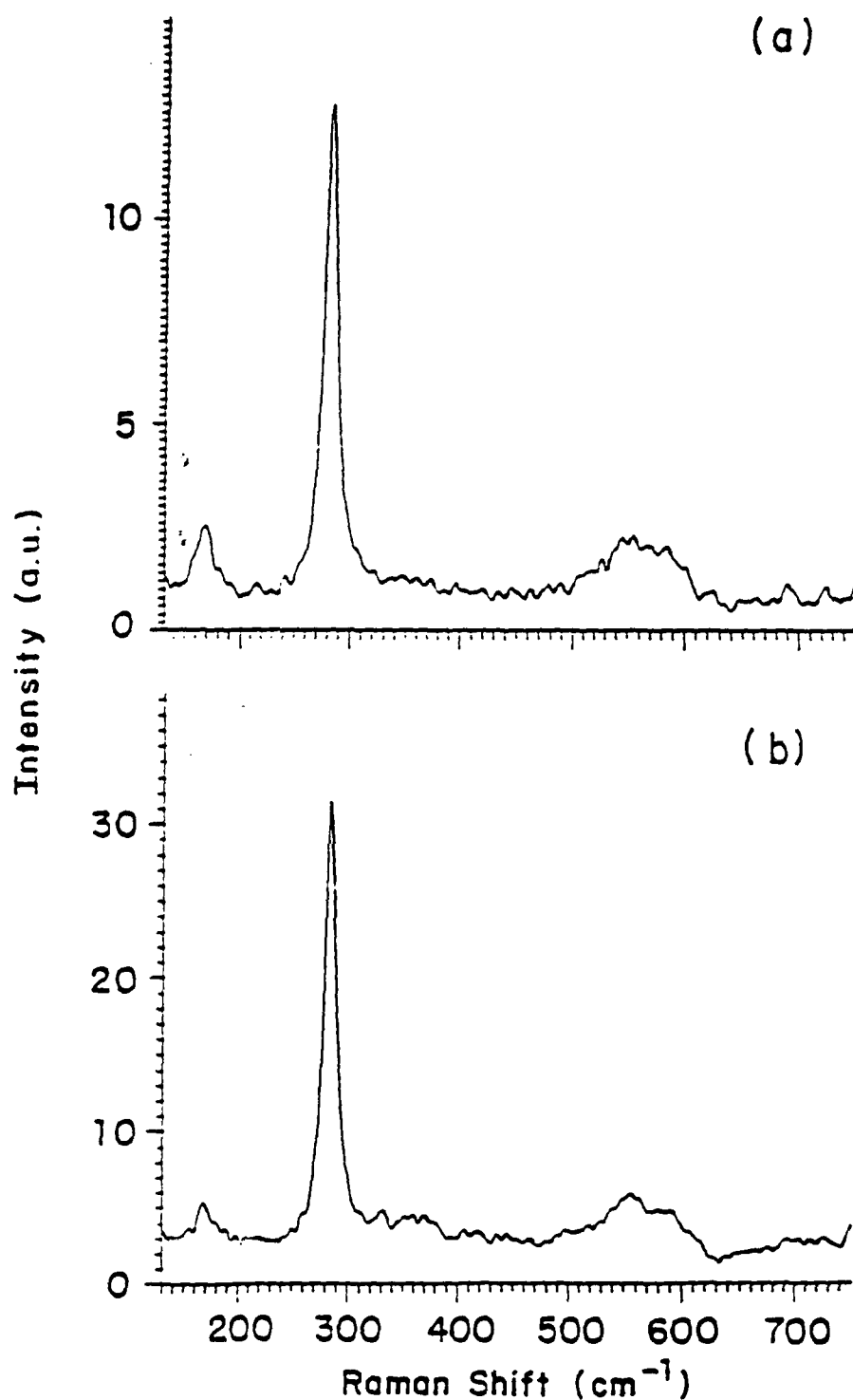


Figure 2. (a) Raman spectrum taken after laser irradiation of CuCl_x -on-Cu film in the presence of chlorine (4880 Å, 20 mW during scan, 5 μm scan rate, 10 Torr Cl_2 , 20 mW for spectrum). (b) Raman spectrum of CuCl_2 (anhydrous cupric chloride powder) at room temperature (4880 Å, 20 mW).

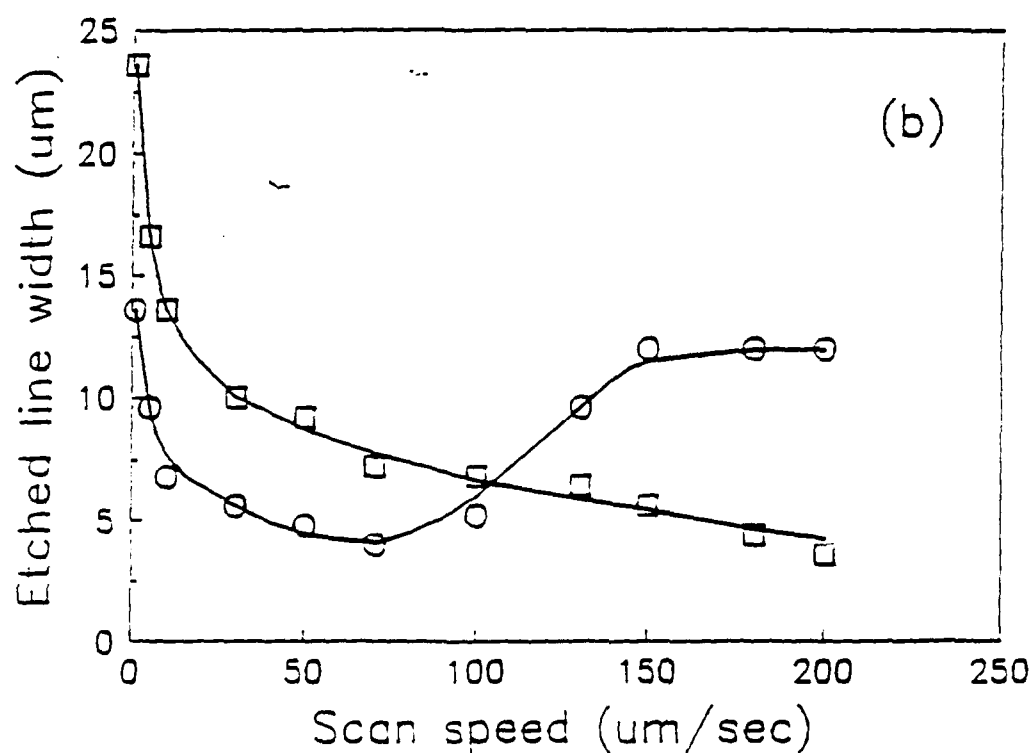
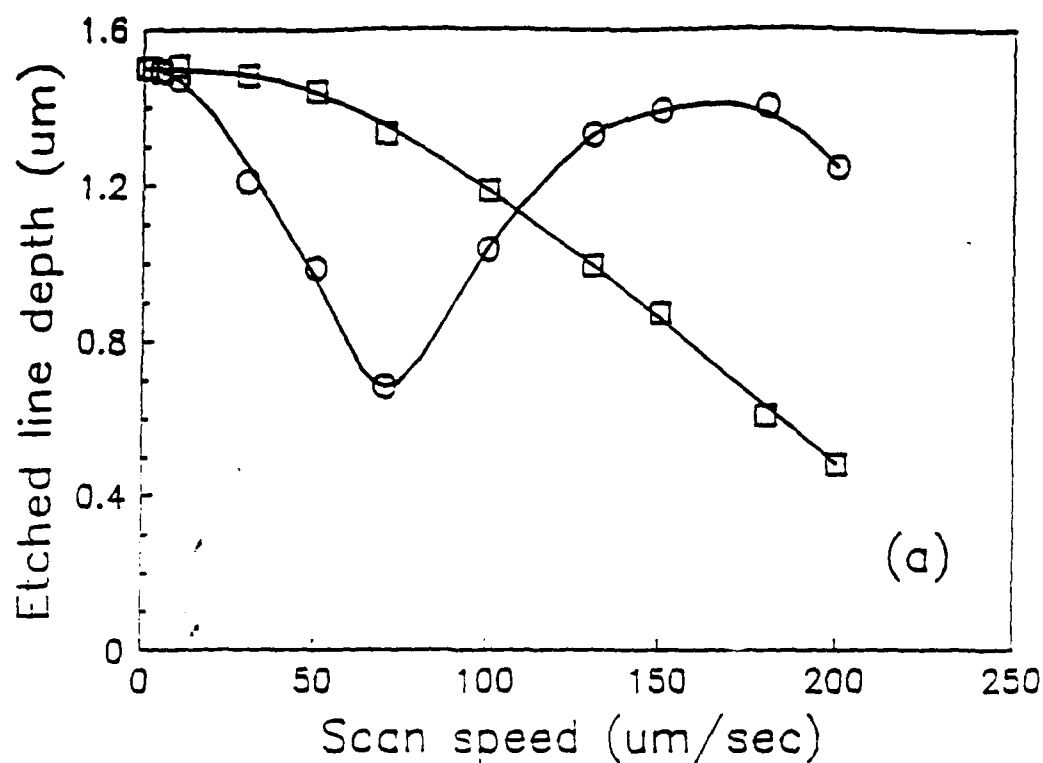


Figure 3. The (a) depth and (b) width of the etched copper features after copper chloride removal for 400 mW of 4880 Å radiation incident on 1.5 μm-thick passivated copper films (15 min oxidation at 150°C) for chlorine pressures 10 Torr (circles) and 120 Torr (squares). There is partial desorption of the copper chlorine product for scan speeds > 80 μm/sec in the 10 Torr run.

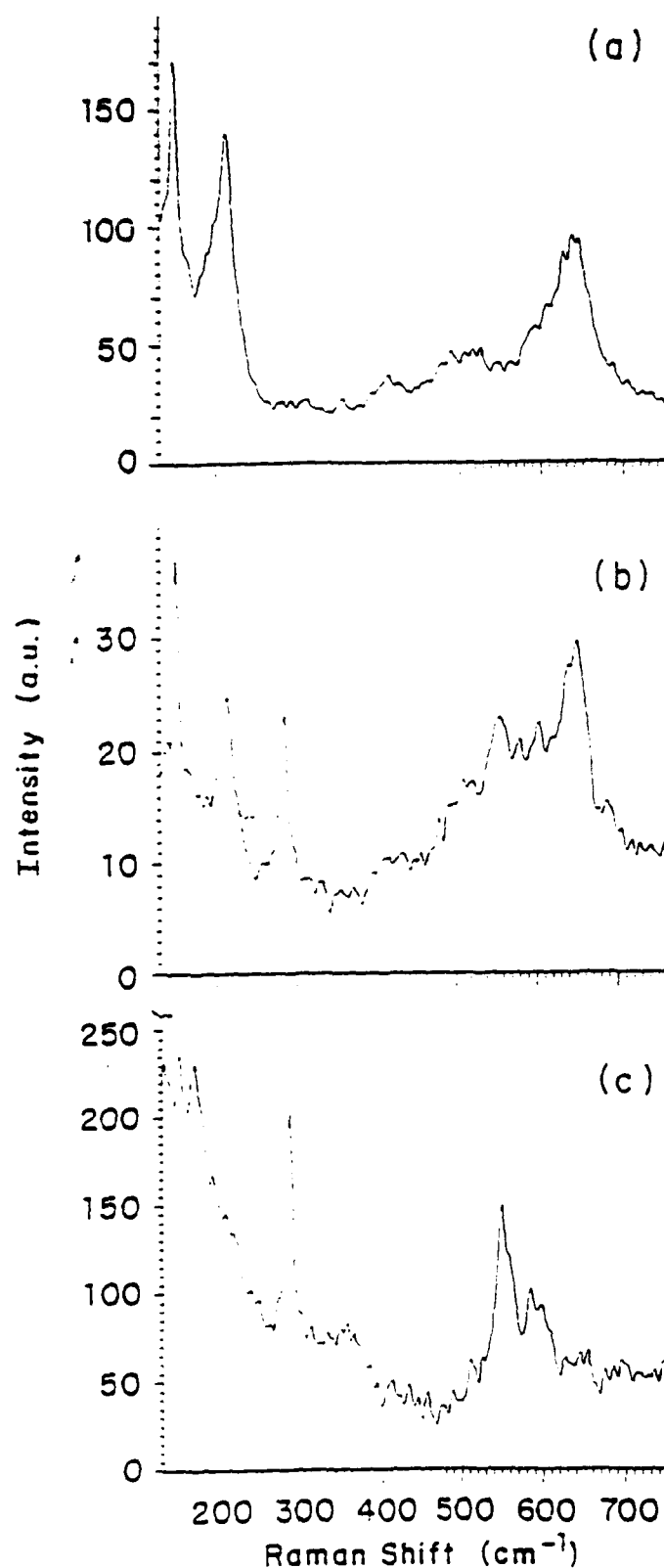


Figure 4. Raman spectra of passivated copper films using 4880 Å (30 minute oxidation at 150°C): (a) before irradiation (20 mW), (b) in real-time during scan in the presence of 10 Torr Cl₂ (5 μm/sec scan rate), (c) reanalysis of (b) after scan, in vacuum (20 mW).

3. Ultrafast Optoelectronic Measurements of Surfaces and Interfaces (Professor David H. Auston and Research Scientist, Dr. Xi-Cheng Zhang)

Research Objective: To develop new high speed optical measurement techniques to characterize the properties of semiconductor interfaces and surfaces.

Accomplishments: We have recently succeeded in developing a new non-contacting method of measuring the properties of space-charge depletion layers at semiconductor surfaces. This technique, which uses femtosecond optical pulses, does not require any electrical contact to the material and is capable of measuring the sign and magnitude of the space charge fields at semiconductor surfaces. The technique is based on the fact that when a femtosecond optical pulse is absorbed at the surface of a semiconductor, a rapid photocurrent transient is produced due to the internal field associated with the space charge depletion layer arising from band bending due to surface states. This current pulse radiates as a picosecond electrical signal and can be detected by time-resolved optoelectronic techniques that we have previously developed. The magnitude and sign of the radiated electrical pulse is determined by the sign and strength of the space charge field. Our detection technique is extremely sensitive and can detect fields of a wide range of values without requiring large optical injected carrier densities. Typical injection levels in our experiments are 10^{13} cm^{-3} , which also ensures that the injected carriers act only as a probe and do not screen the field. We have applied this technique to a wide range of materials and surfaces of type IV(Si, Ge, p-Si, SOS), III-V(GaAs, InP, GaP), and II-VI(CdTe, CdSe, ZnSe) semiconductors. The technique works for p-type and n-type samples as well as semi-insulating samples, and clearly shows the dependence of band-bending on dopant type. We are now extending this work to include measurements of strained-layer and epitaxial heterostructure interfaces as well as surface modified samples. This work is being performed in collaboration with Professors W. Wang and E. S. Yang.

C. Fundamentals of Processing Gas/Surface Interactions

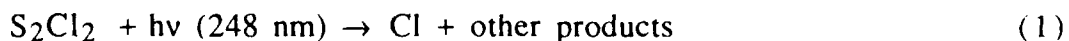
1. Quantum State Resolved Studies of Gas/Surface Chemical Reactions (Professor George Flynn)

Our efforts over the past year have been aimed at the detection of chlorine atoms and studies of their chemical reactions; the production and detection of hot electron/molecule collisions by a novel new technique; and the study of energy exchange between molecules and hot surfaces. These experiments are providing data of fundamental interest for polymer etching, semiconductor surface etching and preparation, and plasma etching environments.

a. Chemical Dynamics of the Reaction between Chlorine Atoms and Deuterated Cyclohexane

Product energy disposal in chemical reactions has been widely studied both experimentally and theoretically.¹ Modern laser spectroscopic techniques allow the determination of both rotational and vibrational quantum states of nascent product molecules, while molecular beam experiments provide information on angular and translational energy distributions. Reactions of chlorine atoms have important applications in atmospheric chemistry,^{2,3} in chemical etching of surfaces,⁴ and in organic chemistry.⁵ We have observed spectroscopically vibrationally and rotationally cold, but translationally hot DCl molecules produced by the reaction of chlorine atoms with deuterated cyclohexane.

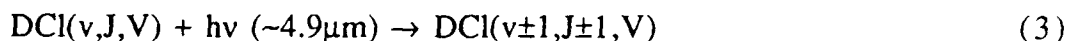
The experimental method employs an excimer laser as pump and an infrared diode laser as probe. Details have been described previously.^{6,7} Briefly, chlorine atoms are produced by excimer laser photolysis of S₂Cl₂ precursor molecules:



This precursor produces a mixture of 78% ground state $^2P_{3/2}$ and 22% excited state $^2P_{1/2}$ Cl atoms⁸ with an average translational energy estimated to be approximately 9.2 kcal/mole (0.4 eV).⁷ the chlorine atoms then react with C_6D_{12} to form DCl:



The rate constant for the corresponding hydrogen atom reaction is $3.1 \times 10^{-10} \text{ cm}^3\text{-molec}^{-1}\text{-sec}^{-1}$ at room temperature.³ DCl products are probed by time-resolved infrared absorption spectroscopy with a high resolution ($\sim 0.0003 \text{ cm}^{-1}$) lead-salt tunable diode laser:



where v, J , and V are the vibrational quantum number, rotational quantum number, and translational velocity, respectively.

When the diode laser was tuned to a DCl $v=0$ absorption line, large transient signals were observed. At the low pressures used, the time between gas kinetic collisions is roughly 3-3.5 μsec , slower than the observed rise times of 1.5 μsec , and much slower than the detector response time of $\sim 700 \text{ nsec}$. Thus the observed transients are due to direct production of nascent, unrelaxed DCl by reaction (2). Much smaller signals were observed when probing DCl $v=1$ lines, indicating that 90% of the products are formed in the vibrational ground state.

The signal amplitudes for different rotational levels of the vibrational ground state were measured at $t=700 \text{ nsec}$ after the excimer pulse. These data were normalized by diode laser power and relative transition matrix elements⁹ to obtain a rotational Boltzmann distribution with a temperature of $T_{\text{Rot}}=156\pm 35 \text{ }^\circ\text{K}$. In addition, transient Doppler lineshape profiles were measured by taking absorption signals while the diode laser was slowly scanned over an absorption line. The lineshape was well fitted to a Gaussian profile with full width at half maximum(FWHM)= $0.0092\pm 0.001 \text{ cm}^{-1}$, which corresponds to a temperature of $T_{\text{Trans}}=1290\pm 300 \text{ }^\circ\text{K}$. The

linewidth for the $v=0$ P(5) line was found to be identical within experimental error to that of $v=0$ P(2).

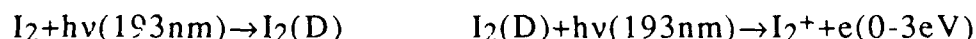
These results clearly represent nonstatistical partitioning of energy into rotationally cold, but translationally hot DCl molecules. This reaction has an exothermicity of 7.9 kcal/mole, with an activation energy estimated at less than 0.5 kcal/mole by comparison with the reaction of Cl with C_5D_{10} .¹⁰ The Cl atom reagent translational energy of 9.2 kcal/mole is easily enough to overcome the activation barrier. The energy available to the reaction products is therefore roughly $E_T(Cl) - \Delta H = 17.1$ kcal/mole, neglecting C_6D_{12} internal energy and Cl atom spin-orbit energy. DCl product rotation accounts for only a fraction $f_R(DCl) = 0.02$ of the available energy. The fraction in DCl translation is $f_T(DCl) = 0.26$, determined from the linewidth data. Momentum conservation allows a rough estimate of $f_T(C_6D_{11}) = 0.10$, leaving $f_I = 0.62$ left for internal motion of C_6D_{11} radical. The collision thus appears to be too short-lived to allow energy randomization of internal and translational degrees of freedom. These results strongly suggest a direct abstraction mechanism with a collinear $C...D...Cl$ recoil geometry for the transition state. The Cl atom does not necessarily have to approach in a linear configuration; even with non-collinear approach, a very small motion of the light D atom can produce a collinear transition state which then rapidly falls apart. The departing DCl products move rapidly away with minimal torque being exerted by the large cyclohexyl radical. Alignment effects such as this have been predicted in trajectory calculations on simple systems.¹¹ Furthermore, similarly cold rotational distributions have been previously observed in hydrogen abstraction reactions of $O(^3P)$ with hydrocarbons.¹² A mechanism in which Cl inserts between C and D would be expected to produce low rotational excitation in DCl even for a nonlinear $C...D...Cl$ geometry; however, such a mechanism is expected to have a high barrier and therefore to be unimportant in the present study. If the collinear hypothesis is correct, a molecular beam experiment should show predominantly backward scattering in the DCl product.

The observation of such a simple mechanism for a reaction between a large gas phase molecule and an atom raises the question as to whether reactions between atoms and thin film surface polymers might also exhibit similar behavior. Efforts to answer this and other questions regarding the reactivity of Cl atoms are continuing in our laboratory.

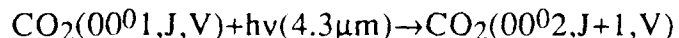
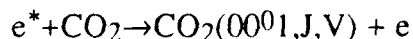
b. Photoproduction and Scattering of Hot Electrons

We have recently discovered a simple method for producing hot electrons and studying their collisions with molecules in the gas phase. A key and novel feature of the experiments is the resolution, 0.0003 cm^{-1} or approximately 4×10^{-8} eV! This compares with standard electron scattering experiments which have a typical energy resolution of about 80 cm^{-1} or 10 meV. The high resolution is obtained by observing the molecular collision partner rather than the scattered electron as is normal in most electron scattering experiments. Such studies can provide fundamental insight into the mechanisms and processes which are important in plasma etching reactors. Considerable interest in this technique has been exhibited by scientists working on plasma etching diagnostics at the IBM East Fishkill facility.

In brief the method is as follows. Electrons are produced in a pulse by two photon excimer laser photoionization of I_2 molecules.



The electrons then collide with CO_2 molecules in the sample, producing vibrationally excited molecules, which are detected using infrared diode laser radiation having a frequency purity of 0.0003 cm^{-1} .



00⁰1 denotes the first antisymmetric stretching vibration of CO₂, but we have in fact detected some six different vibrationally excited states of CO₂ using this technique. J is the rotational angular momentum and V the recoil velocity of the CO₂ due to collisions with e, both of which are measured in the experiment. A brief summary of the results obtained so far is as follows. The electron imparts essentially no angular momentum or translational recoil to the molecule. In essence, the electron is so light that at the energies available in this particular experiment (0-3 eV), it cannot impart any significant momentum to the heavy CO₂. Vibrational energy is quite another matter, however. We find that all vibrational modes are excited relatively efficiently. A particularly intriguing result is that the two Fermi doublets, which are nearly identical mixtures of the 10⁰0 and 02⁰0 vibrational states are not equally excited by these electron collisions. The upper Fermi doublet is in fact excited about ten times more efficiently than the lower Fermi doublet. At present there is no obvious explanation for this observation. The relatively high efficiency of exciting vibrational states is due to the strong interaction of the electron with the molecular electronic structure. Distortions of the electron cloud cause large distortions in molecular geometry since the 17 electron CO₂⁻ ion is bent while the 16 electron CO₂ neutral is linear.

Future efforts will be aimed at using other sources to produce photoelectrons in an attempt to make more monoenergetic electrons. Studies of other molecular systems of interest in plasma etching environments will be made using both I₂ as an electron precursor and other atomic or molecular precursors.

c. Vibrational Energy Exchange at Surfaces

The third project which we have been pursuing is the study of the vibrational energy distribution of molecules produced as the result of a collision between a gas phase molecule and a hot surface. We have used diode laser probing to determine the vibrational temperature of carbon dioxide molecules which are excited when CO₂ collides with a hot platinum mesh. Preliminary data indicates that

all vibrational modes of the CO₂ are excited but there are differences between the temperatures of the three modes. The question arises as to whether similar information can be obtained from collisions occurring on other surfaces, such as silicon. If so, the data obtained should provide fundamental insights into chemical reaction dynamics on surfaces and hence lead to better control of etching processes.

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2. Photochemical and Photophysical Probes of Interfaces (Professor Nicholas J. Turro)

Our research program has explored the use of photochemical processes to characterize the structure and dynamics of reactions which occur at a variety of interfaces. Since interfacial chemistry is critical to many aspects of the microelectronic industry and for the generation of nanostructures, we have emphasized investigations of fundamental processes that will reveal general principles which will be most likely to make a general impact on the field.

In one study we have shown that ketones possess side chains that are normally involved in photochemical reactions in homogeneous solvents undergoing different reactions when adsorbed on zeolites. Rearrangements and disproportionations which do not occur in solvents are the major processes for the ketones adsorbed on zeolites. Exchangeable cations embedded in the internal surface of the zeolite were found to exert a significant influence on the reaction pathways. These results demonstrate the possibilities of changing reaction pathways by adsorption on porous solids and of fine tuning pathways by variation of the framework cations. A paper on this subject has been published in Tetrahedron Letters.

In a second investigation it was shown that the photochemistry of aryl alkyl ketones, which involves a competition of cleavage and side chain reactions, can also be substantially modified by adsorption on zeolites. As in the study discussed above, the reaction pathways are sensitive to the number and type of cations associated with the framework structure. A paper on this subject has been published in Tetrahedron Letters.

The conformation of polymers adsorbed at interfaces plays a major role in the behavior of these materials. For example, the rate of solubilization, a process of importance in determining the feasibility and resolution of photoresists, is dependent on the details of the polymer conformation and interactions with an interface. We investigated the conformation of polyacrylic acid adsorbed on alumina by use of a photoluminescence probe. The probe monitored the shape of the polymer (coiled versus extended). The results

demonstrated that the stretched polymer dangles into the aqueous phase, whereas the coiled polymer covers the interface. Variation of the pH allows interconversion of the coiled and stretched forms. A paper describing this research has been accepted by Colloids and Surfaces.

III. PUBLICATIONS

B. B. Hu, X.-C. Zhang, D. H. Auston and P. R. Smith, "Free Space Radiation from Electro-Optic Crystals," submitted to Appl. Phys. Lett.

D. H. Auston and P. R. Smith, B. B. Hu, J. Darrow, X.-C. Zhang, "Optically-Steerable Photoconducting Antennas," submitted to Appl. Phys. Lett.

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IV. PRESENTATIONS

ANNUAL MEETING OF THE LASERS & ELECTRO-OPTICS SOCIETY OF THE IEEE, Santa Clara, November 1988. "Lightwave Device Research at Columbia University's Center for Telecommunications Research," D. H. Auston (invited talk).

ANNUAL MEETING OF THE OPTICAL SOCIETY OF AMERICA, Santa Clara, November, 1988. "Femtosecond Optoelectronics," D. H. Auston (invited tutorial talk).

ANNUAL MEETING OF THE OPTICAL SOCIETY OF AMERICA, October, 1989, "Femtosecond Electrical Pulses in Free Space," B. B. Hu, X.-C. Zhang, D. H. Auston.

CONFERENCE ON LASERS & ELECTRO-OPTICS, Baltimore, April, 1989. "Generation & Detection of Femtosecond Electromagnetic Pulses," D. H. Auston (invited talk).

IBM EAST FISHKILL FACILITY, March 14, 1989, "Optical Probing in Semiconductor Processing," I. Herman.

ALLIED-SIGNAL, December 6, 1988, "Laser Processing and Diagnostics for Semiconductors," I. Herman.

AMERICAN CHEMICAL SOCIETY MIDWEST MEETING, November 17, 1988, "Laser Chemical Processing of Semiconductors," I. Herman (invited talk).

INTERNATIONAL LASER SCIENCE CONFERENCE/AMERICAN VACUUM SOCIETY NATIONAL MEETING, Atlanta, GA, October 4, 1988. "Excimer Laser Photochemical Vapor Deposition of Germanium-Silicon Alloys: Thin Film Growth and Characterization," I. Herman

NATIONAL COMMUNICATIONS FORUM 1988

"High-Speed Optical Networks"(invited talk), X.-C. Zhang; Proceedings of the National Communications Forum 42, 1651 (1988).

MATERIALS RESEARCH SOCIETY MEETING, November 1988.

"Laser Surface Chemistry of Metal Alkyls," R. M. Osgood, Jr.

AMERICAN VACUUM SOCIETY MEETING, November 1988.

"Laser Applications in Surface Science," R. M. Osgood, Jr. (plenary talk); "Photogenerated-Carrier Induced Surface Reactions: Oxygen on GaAs," D. Podlesnik.

AMERICAN VACUUM SOCIETY MEETING, Atlanta, Georgia, October 1988, "Ultraviolet Laser Induced Photochemistry on GaAs surfaces," M. T. Schmidt, C. F. Yu, Z. Wu, D. V. Podlesnik, E. S. Yang, and R. M. Osgood, Jr.

32nd INTERNATIONAL SYMPOSIUM ON ELECTRON, ION, AND PHOTON BEAMS, Ft. Lauderdale, Florida, 1988, "Laser-Controlled Surface Modification of Semiconductors," D. V. Podlesnik, M. T. Schmidt, C. F. Yu, and R. M. Osgood, Jr.

OPTICAL SOCIETY OF AMERICA, CONFERENCE ON LASERS AND ELECTRO-OPTICS, Washington, D.C., 1988, "In situ Processing for GaAs Devices Using Ultraviolet Laser Formed Oxides," M. T. Schmidt, D. V. Podlesnik, C. F. Yu, E. S. Yang, and R. M. Osgood.

YALE SEMINAR, December 1988, "Laser Processing Physics and Devices," R. M. Osgood, Jr.

NIST SEMINAR, January 18, 1989, Washington D.C., "Photon Processing of Materials: Techniques and Basic Surface Physics," R. M. Osgood, Jr.

MAX PLANCK INSTITUT FUR PHYSICAL AND BIOLOGISCHE CHEMIE,
March 12, 1989, Gottingen, Germany, "Laser Surface Interactions and
Applications," R. M. Osgood, Jr.

IBM, March 13, 1989, Yorktown, NY., "The Surface Spectroscopic
Study of Organometallic Molecules," Ping Shaw.

RUTGERS UNIVERSITY, March 15, 1989, New Jersey, "Laser-
Controlled Processing for Microelectronics," Lectures on
Interdisciplinary Areas of Laser Science, Dragan Podlesnik.

MAX PLANCK INSTITUT FUR QUANTENOPTIK, March 21, 1989,
Garching, West Germany, "Laser Surface Interactions and Comments
on Their Applications," R. M. Osgood, Jr.

MIT, May 2, 1989, Cambridge, MA, "Advanced Photon Processing for
VLSI," R. M. Osgood, Jr.

DUPONT, May 16, 1989, Wilmington, Delaware, "Laser Chemical
Processing of Materials," R. M. Osgood, Jr.

EASTMAN KODAK, CORPORATE RESEARCH LAB., June 7, 1989,
Rochester, NY, "Laser Processing of Materials for Optoelectronic
Devices," D. V. Podlesnik.

FRITZ-HABER-INSTITUT DER MAX-PLANCK-GESELLSCHAFT, June 15,
1989, Berlin, Germany, "Laser-Surface Chemical Interactions and
Applications," R. M. Osgood, Jr.

THIRD INTERNATIONAL SYMPOSIUM ON SURFACE MODIFICATION
TECHNOLOGIES, June 20, 1989, Neuchatel, Switzerland, "Laser-
Controlled Modification of Semiconductor Surfaces," D. V. Podlesnik.

IBM, June 28, 1989, Fishkill, NY, "Photochemistry of Adsorbed
Oxygen on GaAs," D. V. Podlesnik.

IBM, T. J. WATSON LABORATORIES, July 19, 1989, Yorktown Heights.
"Laser-Controlled Processing of Electronic Materials," D. V. Podlesnik.

GORDON RESEARCH CONFERENCE ON PHYSICAL ORGANIC CHEMISTRY,
June 11-16, 1989, "Organic Chemistry in Restricted Spaces," N. J.
Turro.

GORDON RESEARCH CONFERENCE ON ORGANIC PHOTOCHEMISTRY, July
16-21, 1989, "Photochemical Reactions in Restricted Spaces," N. J.
Turro.

NEW YORK UNIVERSITY, April 28, 1989, "Photochemistry of Organic
Molecules Adsorbed on Zeolite Molecular Sieves," N. J. Turro.

UNIVERSITY OF CHICAGO, October 17, 1988, "Radical Pairs and
Biradicals in Constrained spaces," N. J. Turro.

INTERNATIONAL CONFERENCE ON INTERFACE SCIENCE, Perdido Beach,
Alabama, September 18-23, 1989, "Organic Chemistry in Microscopic
Reactors," N. J. Turro.

AMERICAN CHEMICAL SOCIETY NATIONAL MEETING, Symposium on
Chemical Rate Processes in Condensed Phases, Miami Beach, Florida,
September 10-15, 1989, "Chemical, Spin and Molecular Dynamics in
Restricted spaces," N. J. Turro.

AMERICAN CHEMICAL SOCIETY NATIONAL MEETING, Symposium on
Chemistry in Constrained Spaces, Miami Beach, Florida, September
10-15, 1989, "Photochemical Reactions in Constrained Spaces," N. J.
Turro.

MATERIAL RESEARCH SOCIETY, Spring Meeting in San Diego, April
1989, "Interdiffusion between substrates and YBaCuO Films Formed
by Rapid Thermal Annealing of Cu/BaO/Y₂O₃ Layered Structures,"
Q. Y. Ma, C. F. Yu, X. Wu, M. T. Schmidt, E. S. Yang, and Chin-An Chang.

THIRD ANNUAL CONFERENCE ON SUPERCONDUCTIVITY AND APPLICATIONS, Buffalo, NY, September, 1989, "Processing and Substrate Effects on YBaCuO Thin Films Formed by Rapid Thermal Annealing of Cu/BaO/Y₂O₃ Layered Structures," Q. Y. Ma, M. T. Schmidt, T. J. Licata, D. V. Rossi, E. S. Yang, Chin-An Chang and C. E. Farrell.

IEEE DEVICE RESEARCH CONFERENCE, MIT, June 22, 1989, "Band structure engineering for electron tunneling in heterostructures," R. Beresford, L.F. Luo, and W.I. Wang.

MOLECULAR BEAM EPITAXY WORKSHOP, North Carolina State University, Raleigh, N.C., September 1989, "Surface structures of AlGaSb," J. Piao, R. Beresford, and W. I. Wang.

INTERNATIONAL ELECTRON DEVICE MEETING (IEDM), Washington, D.C., December 1989, "Interband tunneling in polytype heterostructure for high speed devices," R. Beresford, L.F. Luo, K. F. Longenbach, and W.I. Wang.

INTERNATIONAL CONFERENCE ON NARROW GAP SEMICONDUCTORS, June 12 - 16, 1989, Gaithersburg, MD, "Narrow gap InAs for Heterostructure Tunneling Devices," R. Beresford, L. F. Luo, and W. I. Wang.

IBM WATSON LABORATORIES, Yorktown Heights, N.Y., May 25, 1988, "Diode Laser Probes of Collisional Relaxation," G. W. Flynn.

NAVAL RESEARCH LABORATORY, Washington, D.C., August 19, 1988, "Diode Laser Probes of Collisional Relaxation," G. W. Flynn.

UNIVERSITY OF PENNSYLVANIA, Philadelphia, PA, October 27, 1988, "Diode Laser Probes of Collisional Relaxation," G. W. Flynn

UNIVERSITY OF CALIFORNIA, Los Angeles, CA, November 14, 1988, "Diode Laser Probes of Collisional Relaxation," G. W. Flynn.

UNIVERSITY OF CALIFORNIA, Irvine, CA, November 15, 1988, "Diode Laser Probes of Collisional Relaxation," G. W. Flynn.

IBM ALMADEN RESEARCH LABS, San Jose, CA, November 16, 1988, "Diode Laser Probes of Collisional Relaxation," G. W. Flynn.

YALE UNIVERSITY, New Haven, CT, January 26, 1989, "Super High Resolution Studies of Chemical and Collision Dynamics," G. W. Flynn.

POLYTECHNIC UNIVERSITY, Brooklyn, NY, February 1, 1989, "Super High Resolution Studies of Chemical and Collision Dynamics," G. W. Flynn.

SOUTHERN ILLINOIS UNIVERSITY, Carbondale, IL, March 1, 1989, "Super High Resolution Studies of Chemical and Collision Dynamics," G. W. Flynn.

UNIVERSITY OF KANSAS, Lawrence, KA, March 3, 1989, "Super High Resolution Studies of Chemical and Collision Dynamics," G. W. Flynn.

JOINT INSTITUTE FOR LABORATORY ASTROPHYSICS, University of Colorado, April 11, 1989, "Super High Resolution Studies of Chemical and Collision Dynamics," G. W. Flynn.

CONFERENCE ON LASERS AND ELECTROOPTICS, Baltimore, Md., April 25, 1989, "High Resolution Lasers in The Study of Chemical Dynamics," G. W. Flynn.

CONSOLIDATED EDISON LECTURE, Columbia University, New York, NY, May 3, 1989, "Energy Science from Confucius to Buck Rogers," G. W. Flynn.

GORDON CONFERENCE ON MOLECULAR ENERGY TRANSFER, Wolfboro, NH, July 13, 1989, "Lasers from Rabi to Javan: Super High Resolution Studies of Molecular Collisions and How They Came to Be," G. W. Flynn.

WORKSHOP ON DYNAMICS OF LASER-INDUCED MOLECULAR PROCESSES, Gottingen, West Germany, September 25, 1989, "Super High Resolution Studies of High Energy Molecular Relaxation Phenomena," G. W. Flynn.

SWISS FEDERAL INSTITUTE OF TECHNOLOGY (ETH), Zurich, Switzerland, September 29, 1989, "Chemical and Collision Dynamics from Diode Laser Probes," G. W. Flynn.

V. PATENTS/INVENTIONS

E. R. Fossum, R. E. Colbeth, and J. I. Song, "GaAs imager with recessed pixel isolation," disclosed July 1989.

E. R. Fossum, D. V. Rossi, and J. I. Song, "Resistive gate time delayed integration IR imager architecture," disclosed July 1989.

E. R. Fossum and S. Borodach, "Drift multiplexer for fiber-optic communications," disclosed July 1989.

E. S. Yang and Q. Y. Ma, "Method of patterning superconducting films in which superconductivity is inhibited by diffusion of impurities," Patent Filing No 391109.

VI. RESUMES OF PRINCIPAL INVESTIGATORS

- A. David H. Auston
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- C. Eric R. Fossum
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BASc: 1962 University of Toronto, Engineering Physics, Graduated with honors.

Professional Experience:

- 1987-present:** Professor of Electrical Engineering, Applied Physics and Nuclear Engineering, Columbia University.
1969-1987: Member of Technical Staff at AT&T Bell Laboratories, Murray Hill, NJ, and Head of the High Speed Materials and Phenomena Research Department in the Physics Division.
1979: Visiting professor for six months in the Groupe de Physique des Solides de l'Ecole Normale Supérieure, Paris, France.
1969: Acting assistant professor at University of California, Berkeley. Taught laboratory and lecture course in physical electronics.
1963-1966: Research Physicist, General Motors Defense Research Laboratory, Santa Barbara, CA. Developed new millimeter-wave instrumentation for plasma diagnostics.

Professional Activities:

- 1985-86:** Elected member of the Administrative Committee and chairman of the publications committee of the Lasers and Electro-optics Society of the IEEE.
1986-present: Editor of the Springer-Verlag series of texts on Electronics and Photonics.
1986-present: Associate editor, Optics Letters.
1985-1987: Advisor of the Rutgers University Center for Science Education.
1985-87: Member of the Technical Council and chairman of the Technical Group on Optoelectronics of the Optical Society of America.
1985-89: Co-chairman and member of the Steering Committee of Conference on Lasers and Electro-optics.
1985-86: Lasers and Electro-optics Society of the IEEE; Elected member, Administrative Committee; chairman, publications committee.
1985: Advisor to the Smithsonian Institution on the 25th anniversary of the laser.
1984: Co-chairman, 1984 Conference on Ultrafast Phenomena, Monterey, CA.
1981: Chairman, Gordon Research Conference on Nonlinear Optics, and Lasers, Wolfeboro, NH.

Awards:

- 1985:** R.W. Wood Prize of the Optical Society of America in recognition for original contributions to picosecond optoelectronics.
1986: First Walter Schottky Lecturer of the University of Aachen, FRG.
1988: Fellow of the Optical Society of America.
1989: Elected to the National Academy of Engineering.

Books:

Ultrafast Phenomena IV, Editors: D. H. Auston and K. B. Eisenthal, Springer-Verlag, Heidelberg, (1984); *Picosecond Optoelectronics*, D. H. Auston, Springer-Verlag, Heidelberg, (in preparation); *Picosecond Optoelectronics: A Reprint Volume*, IEEE Press (in preparation).

Patents:

7

B. GEORGE W. FLYNN

Department of Chemistry
Columbia Radiation Laboratory
Columbia University
253 Eng. Ter., 120th and Amsterdam Ave.
New York, NY 10027

(212) 854-4162

Education:

Ph.D., Harvard University, 1965
M.A., Harvard University, 1962
B.S., Yale University, 1960

Professional History:

Academic Positions:

Professor, Department of Chemistry, Columbia University, 7/76 - present
Thomas Alva Edison Professor, Columbia University, 7/86 - 6/89
Visiting Scientist, Massachusetts Institute of Technology, Spring 1975
Associate Professor, Columbia University, 7/72-6/76
Assistant Professor, Columbia University, 1/67-6/72

Research Appointments:

Panel for Chemical Physics, National Bureau of Standards, 1987-90
Visiting Scientist, Rowland Institute for Science, Inc., 7/1/82 - 8/31/82
Co-Director, Columbia Radiation Laboratory 7/84 - present.
Director, Columbia Radiation Laboratory, 1/79 - 6/84
Member, Columbia Radiation Laboratory, 7/75 -
Consultant Brookhaven National Laboratories, 10/1/78 -
Research Collaborator, Brookhaven National Laboratories, 3/69 - 9/78
Guest Associate Chemist, Brookhaven National Laboratories, 11/68 - 3/69

Honors and Fellowships:

Distinguished Visiting Scientist, Joint Institute for Laboratory Astrophysics,
April, 1989.
Distinguished Summer Lecturer in Physical Chemistry, Northwestern
University, July 1986
Fellow, American Physical Society, 1984
A. Cressy Morrison Award in Natural Sciences, 1983; NY Academy of Sciences
Reilly Lecturer, University of Notre Dame, April 1983
William Pyle Phillips Lecturer, Haverford College, October 1982
Harold C. Urey Award, 1982
John Simon Guggenheim Memorial Fellow, 1974-75
12th Mark Van Doren Award, 1973
Alfred P. Sloan Research Fellow, 1968 - 70
NSF Postdoctoral Fellowship, 1964-65
NSF Predoctoral Fellowship, 1960-64
B.S. Degree Summa Cum Laude with exceptional distinction in Chemistry

Professional Memberships:

American Physical Society, American Chemical Society, Sigma Xi
New York Academy of Sciences Division of Physical Chemistry
American Chemical Society, Executive Committee, 9/78-9/81
Earle K. Plyler Award Committee, American Physical Society, 1984-88
Division of Chemical Physics, American Physical Society,
Executive Committee, 1987-88

C. ERIC R. FOSSUM

Assistant Professor
Department of Electrical Engineering
1334 S. W. Mudd
New York, NY 10027

(212) 854-3104

Education:

Ph.D., Yale University, 1984

M.S., Yale University, 1980

B.S., Trinity College, 1979

Professional History:

1989-present: Associate Professor, Department of Electrical Engineering, Columbia University
1985 - 1989: Assistant Professor, Department of Electrical Engineering, Columbia University
1983: Acting Instructor, Yale University, New Haven, CT
1981-1983(Summers): Member of the Technical Staff, Hughes Aircraft Company Missile Systems Group

Special Grants, Awards and Appointments:

Distinguished Visiting Scientist, Jet Propulsion Laboratory, 1989 - present
Analog Devices Career Development Award, 1988
Consultant, IBM Research, Kulite Semiconductor, 1985 - present
NSF Presidential Young Investigator Award, 1986
IBM Faculty Development Award, 1984-1985
Henry Prentiss Becton Prize for Excellence in Engineering and Applied Science, 1984
Howard Hughes Graduate Fellowship, 1981-1984
Division Invention Award, Hughes Aircraft Co., 1983
IBM Graduate Fellowship, 1980-1981
Yale University Fellowship, 1979-1980
Graduated with Honors in Physics; President's Fellow in Physics; Senior Physics Prize, 1979

Memberships and Professional Activities:

APS, AVS, IEEE, and SPIE
Organizer and Instructor: 1988 MSL Short Course on Charge-Coupled Devices
Program Committee Member: 1987 and 1988 IEEE Semiconductor Interface Specialists' Conferences
Organizer and Chairman: 1986 IEEE Workshop on Charge-Coupled Devices

Volunteer Activities:

1989: Chairman, Task Force on Double Discovery Center
1987 - present: Member of the Board, Double Discovery Center
1986 - present: Mentor, Career Beginnings Program

Research Focus:

Marriage of new materials, device structures, and circuits for advanced electro-optical systems. The primary thrust of this research is in charge-coupled devices (CCD'S) and optical interconnections.

D. IRVING P. HERMAN

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Columbia University
217 S. W. Mudd
New York, NY 10027
(212) 854-4950

Education:

Ph.D., Physics, Massachusetts Institute of Technology, 1977
B.S., Physics, Massachusetts Institute of Technology, 1972

Professional History:

1986 - present: Associate Professor of Applied Physics, Columbia University
1981 - 1986: Section Leader, Special Studies Group, Physics Department, LLNL
1977 - 1986: Professional Staff Member, University of California, Lawrence Livermore National Laboratory
1977: Postdoctoral Scientist, M.I.T., Physics Department
1972 - 1977: Fannie and John Hertz Predoctoral Research Fellow, M.I.T., Physics Department

Professional Activities:

1988: Organizing Committee for Lasers in Electronics Processing, CLEO 1989 Meeting
1986: Co-organizer and Chairman, Symposium on Photon, Beam and Plasma Stimulated Chemical Processes on Surfaces, Materials Research Society National Meeting
1985 - present: Member of Advisory and Program Committee, International Laser Science Conference
1983 - 1988: Thesis Advisor, Ph.D. Candidates, Department of Applied Science, University of California at Davis, Livermore Campus
1983: Symposium Organizer and Chairman, International Conference on Lasers, Laser Isotope Separation Symposium

Special Grants, Awards and Appointments:

1977: National Research Council Postdoctoral Fellow (declined)
1972 - 1977: Fannie and John Hertz Predoctoral Fellow
1972: Phi Beta Kappa
1972: National Science Foundation Fellowship (declined)

Professional Memberships:

American Physical Society
Materials Research Society
American Chemical Society
Institute of Electrical Engineers

Research Areas:

Optical physics of the solid state, Molecular physics,
Optical spectroscopy and its applications

Publications: 47

E. RICHARD M. OSGOOD, JR.
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Microelectronics Sciences Laboratories
Columbia University
Department of Electrical Engineering
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Phone: (212) 854-4462

Education:

Ph.D., Massachusetts Institute of Technology, 1973
M.S., Ohio State University, 1968
B.S., U.S. Military Academy, 1965

Professional History:

1988-present: Higgins Professor of Electrical Engineering and Applied Physics,
Columbia University
1982-1987: Professor, Departments of Applied Physics and Electrical Engineering,
Columbia University
1986-present: Director, Columbia Microelectronics Science Laboratories
1984-present: Co-Director, Columbia Radiation Laboratory
1983 - 1986: Acting Director, Columbia Microelectronics Sciences Laboratories
1981 - 1982: Associate Professor, Department of Electrical Engineering,
Columbia University
1980 - 1981: Project Leader, Direct-Write Processing Program, Lincoln Laboratory, MIT
1973 - 1980: Staff Member, Lincoln Laboratory, Massachusetts Institute of Technology
1976(August): Visiting Scientist, Los Alamos Scientific Laboratory
1966 - 1969: Research Officer (Capt.), U.S.A.F. Avionics Laboratory
1965 - 1966: Research Officer, U.S.A.F., Materials Laboratory

Special Grants, Awards, and Appointments:

John Simon Guggenheim Fellowship, 1989
Fellow, Institute of Electrical and Electronic Engineers (IEEE)
Editorial Board, Laser Focus Magazine, 1970 -
Co-Editor, Applied Physics, 1983 -
Consultant, industrial and national laboratories
Advisory Board, MIT Spectroscopy Lab
Organizer, First and Third Materials Research Society Symposium on Laser Photochemical
Diagnostics and Processing 1982, 1984
Member, Basic Energy Sciences Advisory Committee, DOE, 1989 - present
Member, Board on Army Science and Technology (NAS), 1988 - present
Member, Materials Research Council, Defense Advanced Research Projects Agency, 1984 -
Visiting Board, Los Alamos Scientific Laboratory (Chemistry and Laser Division), 1985 -
Associate Editor, IEEE Journal of Quantum Electronics, 1981 - 1988
Councilor, Materials Research Society, 1983 - 1987
Member, DOE Energy Research Advisory Panel on Advanced Isotope Separation, 1980
Hertz Foundation Predoctoral Fellow at M.I.T., 1970 - 1973
Samuel Burka Award (with Dr. W. Eppers) for the best technical paper at the Air Force Avionics
Lab., 1968

Patents: 5

Publications: 158

Advanced device fabrication techniques; Surface physics and physical chemistry; Optical science

F. NICHOLAS J. TURRO

William P. Schweitzer Professor of Chemistry
Box 610 Havemeyer Hall
Department of Chemistry
Columbia University
New York, NY 10027

(212) 854-2175

Education:

NSF Postdoctoral Fellow, Harvard University, 1963-64 (Paul D. Bartlett, Advisor)
Ph.D., California Institute of Technology, 1963 (George S. Hammond, Advisor)
B.A., Wesleyan University, Connecticut, 1960

Professional Experience:

1981 - present, Wm. P. Schweitzer Professor of Chemistry, Columbia University
1981-84, Chairman, Department of Chemistry, Columbia University
1969-81, Professor of Chemistry, Columbia University
1967-69, Associate Professor of Chemistry, Columbia University
1965-67, Assistant Professor of Chemistry, Columbia University
1964-65, Instructor of Chemistry, Columbia University

Awards:

1987, James Flack Norris Award, Northeastern Section, ACS
1986, Harrison Howe Award, Rochester Section, ACS
1986, Arthur C. Cope Scholar Award, ACS
1984, Honorary D. Sc. Degree from Wesleyan University, Conn.
1984, Phi Lambda Upsilon's Urey Award at Columbia University
1984, Sherman Fairchild Distinguished Scholarship at Caltech
1984, John Simon Guggenheim Memorial Foundation Fellowship (Oxford, England)
1983, U.S. Department of Energy's Ernest Orlando Lawrence Memorial Award
1981, Elected Member, American Academy of Arts and Sciences
1981, Elected Member, National Academy of Sciences
1977, N.Y. Academy of Science Halpern Award in Photochemistry
1974, ACS National Award in Pure Chemistry
1973, Phi Lambda Upsilon's National Fresenius Award in Chemistry
1972, Fellow of the N.Y. Academy of Science
1966-70, Alfred P. Sloan Fellowship

Professional Activities (Present):

Editorial Advisory Boards: *Journal of the American Chemical Society*, *Nouveau Journal de Chimie*, *Spectroscopy Letters*, *Encyclopedia of Physical Science & Technology*, *Journal of Photochemistry*, *Journal of Reactive Intermediates*, *Langmuir*
Member of the National Academy of Sciences Board on Chemical Sciences & Technology
Member of the National Research Council Committee on ONR Chemical Sciences Research Planning
Scientific Committee of the Table Ronde on "Reactivity in Organized Liquid Media" of the Institut Scientifique Roussel, Paris
Guest Editor, Tetrahedron symposium-in-Print: Organic Chemistry in Anisotropic Media

Research Interests:

Surface chemistry
Organic Photochemistry
Polymer Photochemistry
Biophysical Photochemistry

G. WEN I. WANG

Professor of Electrical Engineering and Applied Physics
Columbia University
1320 S.W. Mudd
New York, NY 10027
(212) 854-1748

Education:

Ph.D., Electrical Engineering, Cornell University, Ithaca, NY, 1981
M.E.E., Cornell University, 1979
B.Sc., Physics, National Taiwan University, 1975

Professional History:

1987 - present: Professor, Columbia University
1982 - 1987: Research Staff Member, IBM Research Center, Yorktown Heights, NY 10598
1981 - 1982: Member of the Technical Staff, Microelectronics Research and Development Center, Rockwell International, Thousand Oaks, California 91360
1975 - 1977: Taiwan Military Service (compulsary)

Special Grants, Awards and Appointments:

IBM Outstanding Technical Achievement Award, "Two-dimensional hole gas," 1986

Professional Memberships:

Institute of Electrical and Electronics Engineers
American Physical Society
American Vacuum Society

Patent:

L. L. Chang, L. Esaki, W. I. Wang, "Semiconductor device with hole conduction via strained lattice, " US Patent 4665415, 1987.

Research Interests:

Molecular beam epitaxy
High speed optoelectronic devices
Solid state physics

H. EDWARD S. YANG
Professor and Chairman
Department of Electrical Engineering
Columbia University
1307 S. W. Mudd, 500 W. 120th St.
New York, NY 10027
(212) 854-3120

Education:

Ph.D., Yale University, 1965
M.S.E.E., Oklahoma State University, 1961
B.S.E.E., Taiwan Cheng-Kung University, 1957

Professional History:

1987-present: Chairman and Professor, Department of Electrical Engineering, Columbia University.
July 1975 - present: Professor, Department of Electrical Engineering and Computer Science, Columbia University.
September 1970 - June 1975: Associate Professor, Department of Electrical Engineering and Computer Science, Columbia University.
June 1970 - August 1970; August 1973 - May 1974; July 1978 - June 1979; and September 1983 - December 1983: Visiting Faculty Member, IBM Thomas J. Watson Research Center, Yorktown Heights, New York.
August 1971 - June 1972: Visiting Professor, National Chiao-Tung University, Hsinchu, Taiwan.
July 1965 - June 1970: Assistant Professor, Department of Electrical Engineering and Computer Science, Columbia University.
September 1963 - August 1965: Laboratory Assistant, Yale University, New Haven, Connecticut.
February 1961 - September 1963: Junior and Associate Engineer, IBM Corporation, Poughkeepsie, New York.

Honors and Awards:

Best Paper Award, International Electronic Device Meeting, 1986. (#74 in publication list)

Professional Memberships:

IEEE; Sigma Xi; American Physical Society; Materials Research Society

Books:

E. S. Yang, "Current Saturation Mechanisms in Junction Field-Effect Transistors," in *Advances in Electronics and Electronic Physics*, Volume 31, Edited by L. Marton, Academic Press (1972).
E. S. Yang, *Fundamentals of Semiconductor Devices*, McGraw-Hill (1978).
E. S. Yang, "Oscillators," in *McGraw-Hill Encyclopaedia of Science and Technology*, 5th Edition, pp. 668-674 (1982).
E. S. Yang, "Structures and Performance of Polycrystalline Thin-Film Solar Cells," in *Thin Films and Interfaces*, Edited by P. S. Ho and K. N. Tu, North-Holland, New York (1982).
E. S. Yang, *Microelectronic Devices*, McGraw-Hill (1988).

Research Interests:

Metal Semiconductor Interfaces; Novel Device Structures; Surface Physics